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WADC TECHNICAL REPORT 52-204

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HANDBOOK OF ACOUSTIC NOISE CONTROL
VOLUME II. NOISE AND MAN

WALTER A. ROSENBLITH
KENNETH N. STEVENS
AND THE STAFF OF BOLT, BERANEK, AND NEWMAN

JUNE 1953

WRIGHT AIR DEVELOPMENT CENTER

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HANBOOK OF ACOUSTIC NOISE CONTROL
VOLUME II. NOISE AND MAN

Walter A. Rosenblith
Kenneth N. Stevens
and the Staff of Bolt, Beranek, and Newman

June 1953

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FOREWORD

This report was prepared by the firm of Bolt, Beranek, and Newman, Consultants in Acoustics, under Contract No. AF 33(038)-20572, Phase II, Supplemental Agreement No. 1 and CO No. 2 for the Wright Air Development Center. The authors of this report, Messrs. Walter A. Rosenblith and Kenneth N. Stevens, were assisted by the entire staff of Bolt, Beranek, and Newman. The work was conducted under RDO No. 695-63, "Vibration, Sonic and Mechanical Action on Air Force Personnel." Technical supervision of the preparation of the report was the responsibility of Major Horace O. Parrack, United States Air Force, Aero Medical Laboratory, Research Division, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

ABSTRACT

This handbook, comprising two volumes, is intended to provide an overall view of the noise control problem. Classically, the word noise denotes a phenomenon related to hearing, and noise is commonly defined as any unwanted sound. In recent years, noise has come to mean the antithesis of desired signal in any stimulus or form of energy. Thermal motions produce noise in an electronic system and ground reflections may constitute noise in a radar device. Thus it becomes desirable to designate explicitly the subject matter of this handbook, acoustic noise.

There are several ways in which acoustic noise can be undesirable; it can produce pain and damage of personnel, it can interfere with speech communication, and it can cause annoyance and general degradation of environment for work and relaxation. These matters are the subject of Volume II, in which the several subjective responses are analyzed and correlated with properties of the physical stimuli. Volume I is concerned with the stimuli themselves, with their generation and with their control.

However, the problems encountered in the design of a noise control installation are rarely of a purely physical or biological nature, but include the varied factors of economics, operations and planning. Thus the acoustical engineer must be capable of effecting a compromise between these often contradictory considerations. The present volume, therefore, is a guide to assist in making a rational approach to the problems of noise control.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Robert H Blount

ROBERT H. BLOUNT
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

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CHAPTER 15

BIO-ACOUSTICS: TERMINOLOGY AND LITERATURE

15.1 Definitions and Terminology

We include here a number of definitions of terms that are used either in Volume II of this Handbook or in the literature of the field. Most of the terms are related directly to the areas of speech and hearing. There are, however, several more general definitions, some of which are repeated from Chapter 2.

A majority of the definitions have been drawn from the American Standard Acoustical Terminology (1951). These definitions will be marked with an asterisk to distinguish them from those that come from other sources or have been compiled especially for this Handbook.

The definitions of Section 5 (Hearing and Speech) of the American Standard Acoustical Terminology aim essentially at the psychophysics of pure tones and of articulation testing. Those readers who are concerned mainly with the effects of noise of various types upon human behavior will find that the Standard Terminology does not always do justice to the area of their primary interest. It is, of course, hardly to be expected that concepts standardized for stimulus intensities in the comfortable listening range and for laboratory situations should apply without modification to the variegated problems involving the interaction of noise and man.

*<u>Air Conduction</u>. Air conduction is the process by which sound is conducted to the inner ear through the air in the outer ear canal as part of the pathway.

*<u>Articulation (Percent Articulation) and Intelligibility (Percent Intelligibility)</u>. Percent articulation or percent intelligibility of a communication system is the percentage of the speech units spoken by a talker or talkers that is understood correctly by a listener or listeners.

The word "articulation" is customarily used when the contextual relations among the units of the speech material are thought to play an unimportant role: the word "intelligibility" is customarily used when the context is thought to play an important role in determining the listener's perception.

Note 1: It is important to specify the type of speech material and the units into which it is analyzed for the purpose of computing the percentage. The units may be fundamental speech sounds, syllables, words, sentences, etc.

Note 2: The percent articulation or percent intelligibility is a property of the entire communication system: talker, transmission equipment or medium, and listener. Even when attention is focused upon one component of the system (e.g., a talker, a radio receiver), the other components of the system should be specified.

Articulation Score. See articulation.

Articulation Index. See Sec. 16.4.

*Artificial Ear. An artificial ear is a device for the measurement of earphones which present an acoustic impedance to the earphone equivalent to the impedance presented by the average human ear. It is equipped with a microphone for measurement of the sound pressures developed by the earphone.

*Audiogram (Threshold Audiogram). An audiogram is a graph showing hearing loss, percent hearing loss, or percent hearing as a function of frequency.

Audiology. Audiology (literally the "science of hearing") is a field of professional specialization that is primarily concerned with the treatment and measurement of impaired hearing.

*Audiometer. An audiometer is an instrument for measuring hearing acuity. Measurements may be made with speech signals, usually recorded, or with tone signals.

Note: Specifications for a pure tone audiometer for general diagnostic purposes are covered by American Standard Specifications for Audiometers for General Diagnostic Purposes, Z 24.5 - 1951, or the latest revision thereof approved by the American Standards Association, Inc.

*Auditory Sensation Area.

(a) Auditory sensation area is the region enclosed by the curves defining the threshold of feeling and the threshold of audibility as functions of frequency.

(b) Auditory sensation area is the part of the brain (temporal lobe of the cortex) which is responsive to auditory stimuli.

Binaural. Binaural listening is listening with two ears. Binaural listening may be either diotic (same stimulus to both ears) or dichotic (different stimuli to the two ears).

Bio-Acoustics. Bio-Acoustics is the field that deals, in the broadest sense, with the interaction of sound fields or mechanical vibratory phenomena with organisms.

*Bone Conduction. Bone conduction is the process by which sound is conducted to the inner ear through the cranial bones.

Composite Noise Rating. The composite noise rating rank orders noise stimuli in residential areas in order to predict the probable reactions they produce among the residents (see Sec. 18.2).

Coupler. See earphone coupler.

Critical Bandwidth. The critical bandwidth is the width of a band of noise (of the continuous type of spectrum) whose energy is equal to that of a given pure tone at its masked threshold. The frequency of the pure tone is equal to the center frequency of the band of noise.

Damage Risk (DR) Criterion. A damage risk (DR) criterion specifies the maximum sound pressure levels of a noise as a function of frequency to which people should be exposed if risk of hearing loss is to be avoided. A DR criterion should include in its statement a specification of such factors as time of exposure, amount of hearing loss that is considered significant, percentage of the population to be protected, and method of measuring the noise (see Sec. 18.4).

*Difference Limen (Differential Threshold) (Just Noticeable Differences). A difference limen is the increment in a stimulus which is just noticed in a specified fraction of the trials. The relative difference limen is the ratio of the difference limen to the absolute magnitude of the stimulus to which it is related.

Diplacusis (Binaural). An observer exhibits the phenomenon of binaural diplacusis when two tones of the same frequency, each presented to a different ear, appear to differ in pitch.

Discrimination Loss. A discrimination loss is given as the difference between 100 per cent and the percentage of words of a PB (phonetically balanced) list that a listener repeats correctly. The PB list must be presented at an intensity such that a further increase in intensity will not yield a higher articulation score.

*Earphone Coupler. An earphone coupler is a cavity of predetermined shape which is used for the testing of earphones. It is provided with a microphone for the measurement of pressures developed in the cavity.

Note 1:.Couplers generally have a volume of 6 cubic centimeters for testing regular earphones and a volume of 2 cubic centimeters for testing insert earphones.

Note 2: Specifications for couplers are given in the Proposed American Standard Method for the Coupler Calibration of Earphones, Z 24.9 - 1949, or the latest revision thereof approved by the American Standards Association, Incorporated.

*Instantaneous Speech Power. The instantaneous speech power is the rate at which sound energy is being radiated by a speech source at any given instant.

*Hearing Loss (HL) (Deafness). The hearing loss of an ear at a specified frequency is the ratio, expressed in decibels, of the threshold of audibility for that ear to the normal threshold. (See American Standard Specification for Audiometers for General Diagnostic Purposes, Z 24.9-1951, or the latest revision thereof approved by the American Standards Association, Incorporated, see also Sec. 16.3.

*Hearing Loss for Speech. Hearing loss for speech is the difference in decibels between the speech levels at which the average normal ear and the defective ear, respectively, reach the same intelligibility, often arbitrarily set at 50 percent.

*Level above Threshold (Sensation Level). The level above threshold of a sound is the pressure level of the sound in decibels above its threshold of audibility for the individual observer.

Level Rank. The level rank is a means of ordering noise stimuli in residential areas on the basis of their octave band levels. When certain correction numbers are applied to the level rank, the composite noise rating is obtained. (See Sec. 18.2).

*Loudness. Loudness is the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud.

Note: Loudness depends primarily upon the sound pressure of the stimulus, but it also depends upon the frequency and wave form of the stimulus.

*Loudness Contours. Loudness contours are curves which show the related values of sound pressure level and frequency required to produce a given loudness sensation for a typical listener.

*Loudness Level. The loudness level, in phons, of a sound is numerically equal to the sound pressure level in decibels, relative to 0.0002 microbar (dyne/cm2), of a simple tone of frequency 1000 cps which is judged by the listeners to be equivalent in loudness.

*Masking. Masking is the amount by which the threshold of audibility of a sound is raised by the presence of another (masking) sound. The unit customarily used is the decibel.

*Masking Audiogram. A masking audiogram is a graphical presentation of the masking due to a stated noise. This is plotted, in decibels, as a function of the frequency of the masked tone.

*Mel. The mel is a unit of pitch. By definition, a simple tone of 1000 cps frequency, 40 decibels above a listener's threshold, produces a pitch of 1000 mels. The pitch of any sound that is judged by the listener to be n times that of a 1-mel tone is n mels.

Minimum Audibel Field (MAF). The minimum audible field is the threshold of audibility for the case where the sound pressure in a plane progressive wave is measured at the position of the center of a listener's head before the head is inserted into the sound field.

Minimum Audible Pressure (MAP). The minimum audible pressure is the threshold of audibility for the case where the sound pressure is measured at the eardrum of the listener.

Monaural. Monaural listening is listening with one ear.

*Noise. Noise is any undesired sound. By extension, noise is any unwanted disturbance within a useful frequency band, such as undesired electric waves in any transmission channel or device.

Noise Rating. See composite noise rating.

Otology. Otology is that branch of medicine that is concerned with diseases of the ear.

Peak Clipping. Peak clipping is a type of amplitude distortion. A peak-clipping or peak-limiting circuit does not pass peaks exceeding some fixed value. (See Sec. 16.4).

*Peak Speech Power. The peak speech power is the maximum value of the instantaneous speech power within the time interval considered.

*Percent Hearing Loss (Percent deafness). The percent hearing loss at a given frequency is 100 times the ratio of the hearing loss in decibels to the number of decibels between the normal threshold levels of audibility and feeling.

Note 1: A weighted mean of the percent hearing losses at specified frequencies is often used as a single measure of the loss of hearing.

Note 2: The American Medical Association has defined percentage loss of hearing for medicolegal use. (See the Journal of the American Medical Association, 133, 396-397).

*Phon. The phon is the unit of loudness level as specified in the previous definitions.

Phonetically Balanced (PB). A PB list is a list of monosyllabic words that contains a distribution of speech sounds that approximate the distribution of the same sounds as they occur in conversational English.

*Pitch. Pitch is that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high, such as a musical scale.

Note 1: Pitch depends primarily upon the frequency of the sound stimulus, but it also depends upon the sound pressure and wave form of the stimulus.

Note 2: The pitch of a sound may be described by the frequency of that simple tone, having a specified sound pressure or loudness level, which seems to the average normal ear to produce the same pitch.

Power Level. Power level is the ratio, expressed in decibels, of the total acoustic power W radiated by a sound source to a reference power P_{ref}. Thus:

$$PWL = 10 \log_{10} (W/P_{ref}).$$

Usually, P_{ref} is taken as 1.0×10^{-13} watt.

Presbycousis. Presbycousis is the condition of hearing loss specifically associated with old age.

Psycho-Acoustics. Psycho-acoustics is that branch of psychophysics in which observers are asked to make judgments when acoustic stimuli are presented to them.

Random Noise. Random noise is a sound or electrical wave whose instantaneous amplitudes as a function of time occur, according to a normal (Gaussian) distribution curve.

Recruitment. Recruitment is a phenomenon associated with certain types of hearing loss in which the loudness of tones appears to increase with intensity more rapidly than normal.

Sensation Level. See level above threshold.

Signal-to-Noise Ratio. Signal-to-noise ratio is the ratio, usually expressed in decibels, of the intensity of a signal to the intensity of a noise that masks or partially masks the signal.

Social Adequacy Index (SAI). The Social Adequacy Index is a number in the range 1 to 100 that attempts to evaluate communicative adequacy or social adequacy for hearing. It can be determined from the hearing loss for speech and the discrimination loss.

*Sone. The sone is a unit of loudness. By definition, a simple tone of frequency 1000 cps, 40 decibels above a listener's threshold, produces a loudness of one sone. The loudness of any sound that is judged by the listener to be n times that of the one sone tone is n sones.

Note 1: A millisone is equal to 0.001 sone.

Note 2: The loudness scale is a relation between loudness and level above threshold for a particular listener. In presenting data relating loudness in sones to sound pressure level, or in averaging the loudness scales of several listeners, the thresholds (measured or assumed) should be specified.

Note 3: The term "loudness unit" has been used for the basic subdivision of a loudness scale based on group judgment on which a loudness level of 40 phons has a loudness of approximately 1000 loudness units. For example, see Fig. 1 of the American Standard for Noise Measurement.

*Sound-Level Meter. A sound-level meter is an instrument including a microphone, an amplifier, an output meter, and frequency weighting networks for the measurement of noise and sound levels in a specified manner; the measurements are intended to approximate the loudness level which would be obtained by the more elaborate ear balance method.

Note: Specifications for sound-level meters for measurement of noise and other sounds are given in the American Standard Sound Level Meters for Measurement of Noise and Other Sounds, Z 24.3 - 1944, or the latest revision thereof approved by the American Standards Association, Incorporated.

*Sound Pressure Level (SPL). The sound pressure level, in decibels, of a sound is 20 times the logarithm to the base 10 of the ratio of the pressure of this sound to the reference pressure. The reference pressure shall be explicitly stated.

Note 1: The following reference pressures are in common use:

(a) 2×10^{-4} microbar (dyne/cm^2).

(b) 1 microbar.

Reference pressure (a) has been in general use for measurements dealing with hearing and sound-level measurements in air and liquids, while (b) has gained widespread use for calibrations and many types of sound-level measurements in liquids.

Note 2: It is to be noted that in many sound fields the sound pressure ratios are not proportional to the square root of corresponding power ratios and hence cannot be expressed in decibels in the strict sense; however, it is common practice to extend the use of the decibels to these cases.

Spectrum Level. The spectrum level of a noise at a specified frequency is the sound pressure level within a band one cps wide centered at the frequency.

Speech Communication (SC) Criterion. A speech communication criterion specifies the sound pressure level and spectrum of a masking noise necessary to guarantee a specified quality of speech communication.

Speech Interference Level (SIL). The speech interference level of a noise is the average, in decibels, of the sound pressure levels of the noise in the three octave bands of frequency 600-1200, 1200-2400 and 2400-4800 cps.

Spondees. A spondee is a two-syllable word with equal stress on both syllables.

*Threshold of Audibility (Threshold of Detectability). The threshold of audibility for a specified signal is the minimum effective sound pressure of the signal that is capable of evolving an auditory sensation in a specified fraction of the trials. The characteristics of the signal, the manner in which it is presented to the listener, and the point at which the sound pressure is measured must be specified.

Note 1: Unless otherwise indicated, the ambient noise reaching the ears is assumed to be negligible.

Note 2: The threshold may be expressed in decibels relative to 0.0002 microbar or to 1 microbar.

Note 3: Instead of the method of constant stimuli, which is implied by the phrase " a specified fraction of the trials", another psychophysical method (which should be specified) may be employed.

*Threshold of Feeling (or Discomfort, Tickle, Pain) (or Tolerance Threshold). The threshold of feeling (or discomfort, tickle, or pain) for a specified signal is the minimum effective sound pressure of that signal which, in a specified fraction of the trials, will stimulate the ear to a point at which there is the sensation of feeling (or discomfort, tickle, pain).

Note 1: Characteristics of the signal and the measuring technique must be specified in every case.

Note 2: This threshold is customarily expressed in decibels relative to 0.0002 microbar or 1 microbar.

Threshold of Detectability (for speech). The threshold of detectability is the speech level at which the listener is just able to detect the presence of speech sounds about half the time without being able to identify any of the individual sounds precisely.

Threshold of Intelligibility (for speech). The threshold of intelligibility is the speech level at which the listener is just able to obtain without perceptible effort the meaning of almost every sentence and phrase of the connected discourse.

Threshold of Perceptibility (for speech). The threshold of perceptibility is the faintest speech level at which the meaning of connected discourse can be followed by trained listeners exerting attentive effort.

Tinnitus. When an observer reports that he hears sounds in the absence of any external acoustic stimulation, he is said to have tinnitus. (Sometimes called "head noises" or "ringing in the ears".)

*Ultrasonics. Ultrasonics is the general subject of sound in the frequency range above about 15 kilocycles per second.

White Noise. White noise is a sound or electrical wave whose spectrum is continuous and uniform as a function of frequency.

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CHAPTER 16

BASIC BIO- AND PSYCHO-ACOUSTIC DATA

16.1 Introduction

The next few chapters deal with man's behavior in response to sound and with the effects of intense sound upon man. To the engineer these problems may not appear to be of great interest. He may feel that there is little he can do about such matters. "You can't deal with the human factor," or, "that's human nature," he may say. Such statements are only too often made just before throwing up one's hands when confronted with a problem involving the interaction of man and his environment. In the pages that follow, we shall attempt to describe certain general features of man's behavior in response to sound.

While we are not trying to give the impression that we can predict the reactions of a particular person when in the presence of certain sounds, we can make useful statements concerning the probability with which we can expect to observe certain reactions to sounds among a large number of individuals. We shall in most cases be able to state the range over which behavior in response to sound can be observed and we may even be able to give a fairly precise description of the way in which the average man would react in response to a great number of noises or sounds that are actually encountered. Even though no single customer in the United States buys the amount of goods that, according to statistics, Mr. Average Citizen and his family will acquire in the course of a year, most manufacturers and department store managers are still very happy to have the statistical information. Such information permits them, and anyone who deals with large numbers of people, to take measures which <u>on the average</u> and <u>in the long run</u> will prove effective and profitable.

This is the principle on which insurance companies operate and pay dividends; they do not know when any one of their clients is going to die, but they are satisfied if they can predict how many among the large number of their clients will die during any period. In other words, anyone who deals with reasonably large numbers of people (or mass production articles, for that matter) may often be satisfied to know how they will behave on the average.

It is true that in some cases we might want to know how a particular individual is going to be affected by noise. We may be able to get the information by further experimentation upon the individual in question or we may have to be satisfied in sharing the frustration of the physicist, who must remain forever ignorant of what happens to a single electron or molecule.

16.2 Responses of Man to Simple Acoustic Stimuli

Introduction. People listen to speech, music, the high whine of mosquitoes, the low rumbling of thunder. They also hear various noises generated by industry, aircraft, PT boats, subways, and other sources of often unwanted sounds. How do we know that one of our fellow citizens hears a given sound? We can obviously ask him and he can tell us; that is, in most cases he can tell us. 'Hearing' is thus linked with or even defined by the occurrence of a verbal response. There arise, however, certain situations, as in the case of infants, animals, or adults who for some reason cannot talk, in which we need a more general definition of hearing. We say that a sound is heard by an organism if the organism reacts or re sponds to it. Assume, for example, that we have control over a sound stimulus. We will say that a person hears this particular sound if, whenever we turn the sound on, our subject responds in a significant number of presentations of the stimulus. The subject may say "I hear it" or lift his finger, or if he is an animal, move toward a previously arranged location.

The problem of determining the effects of noise on man involves several scientific disciplines. We need physicists and acoustical engineers who are able to measure the energy, spectral composition, and temporal characteristics of noises and of stimuli that might be involved in hearing tests. Psychologists will tell us about the various methods by means of which we can determine and measure the reactions of people and animals to sound. Otologists can give people medical examinations of their ears. Meanwhile, physiologists will study the effects of sounds upon animal and human ears and those parts of the nervous system that function in connection with the ear. From research on animals we can learn which part of the organism is most critically affected by what kind of noise and also what kind of protective measures we might possibly adopt. The industrial hydienist, the audiologist,

and the safety engineer have their role to play: they can spot trouble with respect to both noise sources and onset of hearing loss. They can also assist in the adoption of various noise control schemes designed by acousticians and perhaps, in given situations supervise, in cooperation with medical personnel, the wearing of protective devices for the ear.

People often ask the question, "How do we hear?" Many textbook writers on acoustic matters tell us that "the ear can do such and such." Such a statement usually involves certain oversimplifications. We do not know how we hear any more than we know how we see or how we think. All we can do is describe the reactions that people and animals exhibit to certain classes of sound. We can also measure certain mechanical and electrical events that occur inside the ear or in the auditory nervous system when certain sound stimuli are presented. We can go further by removing certain parts of an animal's anatomy and then observe the effects of such removals upon the behavior of the organism as a whole or upon the above-mentioned mechanical and electrical events. Since our definition of hearing involves a reaction or response from an entire organism, we should be careful not to attribute to the ear alone the behavior of the animal or man in response to auditory stimuli.

On one hand certain researchers are now making very painstaking measurements on the electrical and mechanical events that occur in the ear when a given stimulus is presented. On the other hand, it has been conclusively shown that the removal of certain parts of the auditory nervous system abolishes the response to some stimuli even if the animal's ear as such remains intact. Just how much of the ear and how much of the auditory nervous system are involved in certain responses from animals or humans to sound is at the present time largely unknown. We shall later give a brief description of the most important parts of the ear and of the nervous system as they function in response to acoustic stimuli (see Appendix 1).

While we know little about how people hear, we can say a good deal about the kinds of sounds people hear or to which they react. During the last two decades sufficiently precise electroacoustic equipment has become available that we can now produce all sorts of stimuli and measure them with reasonable accuracy. Yet most of our data have been collected on pure tone stimuli, i.e., sounds that correspond to sinusoidal variations in pressure and whose duration is very long compared to the period of a single sinusoid.

Now there is nothing wrong with the use of pure tone stimuli provided they are reasonably* pure. However, we must not conclude that if the law of superposition holds for stimuli, it holds necessarily for responses. The sounds we hear in every day life are certainly not pure tones. Neither speech sounds, nor the notes from musical instruments, nor the sounds made by the breaking of a twig or by jet engines are simple sinusoids. Most of the sounds we encounter in our lives are emitted by sources that have not just single resonances. Human speech, for example, is characterized by the multiple resonances of the vocal cavities. These cavities may be excited by a periodic source, producing an output of high harmonic content, or by a sound source which originates from the turbulent flow of air. The same kind of analysis can be applied to a good many other natural sounds.

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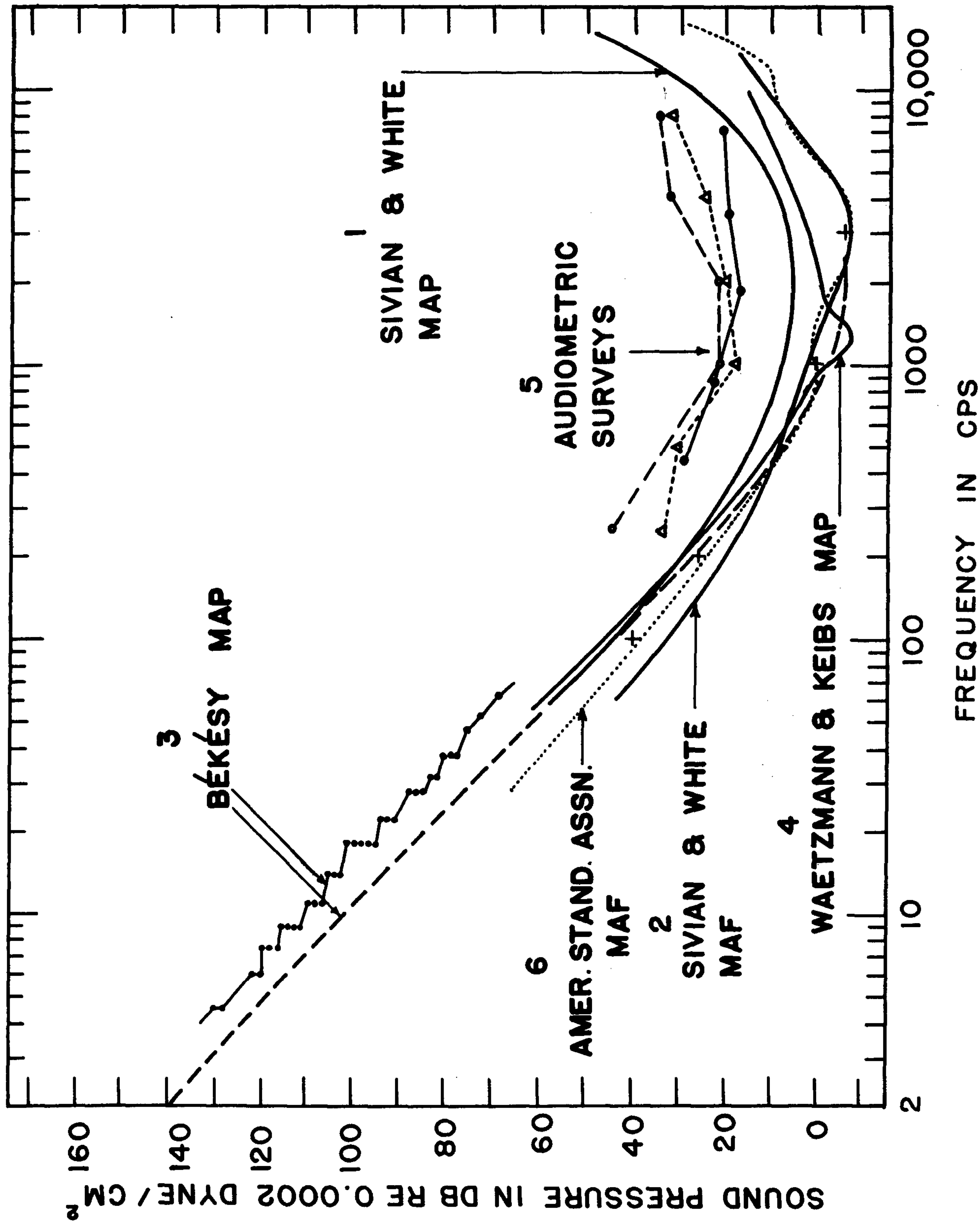
* We use the word "reasonably," otherwise we would have to sound our pure tones from minus infinity to plus infinity since no short tone is ever pure and no pure tone is ever short.

Figure 16.1

Several determinations of the absolute threshold for pure tones are shown. Curves 1 and 2 represent the determinations of minimum audible pressure (MAP) and minimum audible field (MAF) of Sivian and White 1/. Békésy's 2,3/ measurements of MAP in the low and middle frequency range are shown as Curve 3. The MAP data of Waetzmann and Keibs 4/ are given as Curve 4. The results of three audiometric surveys are given as a set of three curves marked 5. The solid line represents the median values for listeners 20 to 29 years of age who took the hearing tests at the Bell Telephone Company's exhibits at the New York and San Francisco World's Fairs in 1938 and 1939 5/. The dashed and dotted curves were obtained, respectively, by the Bell Telephone Laboratories 6/ and by the United States Public Health Service 7/. The American Standards Association 8/ has adopted a "standard" MAF curve (Curve 6), which crosses the 1000 cps ordinate at exactly 0 db SPL, i.e., at a sound pressure of 0.0002 dyne/cm^2. (After J. C. R. Licklider 9/).


1
SIVIAN & WHITE
MAP
5
AUDIOMETRIC
SURVEYS
3
BÉKÉSY MAP
6
AMER. STAND. ASSN.
MAF
2
SIVIAN & WHITE
MAF
4
WAETZMANN & KEIBS MAP
SOUND PRESSURE IN DB RE 0.0002 DYNE / CM²
160
140
120
100
80
60
40
20
0
FREQUENCY IN CPS
2
10
100
1000
10,000

What is so complicated about this, ask those familiar with Fourier analysis. All we have to do is to determine the spectrum of the stimulus and then we can predict what the response to complex sounds is going to be. This is precisely the point where they may go wrong. The kind of behavior we observe in response to complex acoustic stimuli is only rarely predictable from the knowledge of the response to the various isolated components. The listener behaves very much like a non-linear device. We know that over limited ranges we can often replace non-linear systems by approximately linear ones. However, the characteristics of organisms are not only non-linear but also time-varying. It may, therefore, be uneconomical to look for an equivalent linear circuit in order to imitate the behavior of an individual in his reactions to complex sounds.

Let us emphasize our point by giving an example. We first sound a pure tone A, measure its intensity, and have someone judge its loudness. (Let us not enter here into the question as to how one arrives at such a judgment; let us assume that we know how to get loudness judgments from our subject). Now we sound a tone B having the same intensity as A and we again get a loudness judgment from our subject. It is a rather simple matter to measure the intensity of A and B when they are sounded together. However, in order to predict the loudness of the combination, we will need further information. How close in frequency are tones A and B? Do they beat with each other? What is their absolute intensity level? Given these data, we may be able to make a good guess concerning the loudness of the combined pair of stimuli A and B. What, however, if one of the pure tones were replaced by noise? Then we are dealing with a different problem. Or take such phenomena as masking and auditory fatigue which are discussed below. They are again examples of failure of the principle of superposition for responses. This principle predicts man's behavior over a rather narrow range, and must be abandoned, or at best modified, as soon as one goes beyond the boundaries of that range.

With these words of caution, let us proceed to examine some of the available data concerning the response of people to acoustic stimuli such as pure tones, sharp clicks, or wide-band noise.

Audible Frequency Range. The first question we are likely to ask concerns the frequency range over which man responds to stimuli. Disregarding intensity, what is the lowest frequency man recognizes and identifies as a sound and

what is the highest frequency at which young people with normal hearing can still reliably report when the tone is on and when it is off?

Before we answer these two questions let us examine briefly Fig. 16.1 which shows several curves for the threshold of hearing. For the moment we need to concentrate only upon the overall appearance of this family of curves, and not upon any details. We see that man is most sensitive, i.e., able to respond to the weakest stimuli, in the range between 1000 and 3000 cps. As the frequency decreases below 1000 cps or increases above 4000 cps, a higher and higher sound pressure level is necessary to obtain a response.

Below 50 cps and above 15,000 cps, the curve becomes uncertain. It is rather difficult to produce really pure tones of very low frequency and it is rather difficult to measure accurately the stimulus intensity of a tone above 6000 or 8000 cps. What have these considerations to do with the answer to the two questions we have raised above? If our low frequency stimulus is not pure, i.e., if it contains harmonics, we are not sure to what extent the subject has responded to the higher frequencies, and to what extent he has responded to the fundamental. At the high frequency end the situation is different. Here, too, we must make sure that the stimulus is really pure (the output of a beat frequency oscillator around 20 kcps is often contaminated by frequencies which are in the range where man is most sensitive). We must also make sure that (in view of the high intensity needed to get responses) the acoustic transducer does not produce audible subharmonics.

If all these precautions are taken and if one's subjects are picked carefully (i.e., young people without any history of medical involvement of the ear) one arrives at the conclusion that responses to airborne sounds are fairly reliably obtained up to frequencies of about 20 kcps.

Recent experimentation in Germany, England and in this country has shown that people will still say, "I hear something," when bone-conducted sounds of frequencies of as high as 100 kcps are presented at sufficiently high intensity levels 10,11,12/. This is not the place to enter into a discussion of what people mean when they say they 'hear' such sounds. The pitch of these "ultrasonic" stimuli seems rather vague and has been reported to be equal to the pitch of the highest airborne sound the subject can hear. If the

frequency of the sound delivered to the skull is varied, the subject will localize the stimulus alternately at one ear and then at the other.

This discovery may force a more precise definition of what we mean by "hearing" as compared to responding or reacting to sound. It is common knowledge that animals smaller than men respond to higher frequencies. A dog responds to airborne sounds up to perhaps 40 kcps. Recent investigations tell us that the common mouse reacts to frequencies as high as 100 kcps and the researches on the navigation of bats indicate that these animals make very effective use of highly directional beams of high frequency sounds for the detection of obstacles.

At the low frequency end, practically all our data come from Békésy's work 2,3/. His subjects were able to give a response to frequencies as low as 1 cps. Here again, however, there is some uncertainty as to whether the subjects are really "hearing" the 1 cps tone, or whether they are detecting it in some other way. We clearly do not react to slow variations in barometric pressure as sound. Many textbooks state that man's lower frequency limit of hearing lies in the range of 16 to 20 cps. In view of Békésy's work, however, we are probably justified in selecting 1 or 2 cps as the lower frequency limit.

Thresholds of Hearing. Now that we know something about the frequency range over which man responds to sounds, let us examine in more detail the range of stimulus intensities to which he reacts. We have already said that man is not equally sensitive to all frequencies, and we might inquire how much energy or intensity (here defined as the rate of flux of energy) is necessary to get a response at the optimum frequency. We might also ask what is the "dynamic range" of man, and, incidental to this question, we might determine the amount of sound man will stand before he seriously tells us that "this is painful".

Man's auditory threshold is commonly defined as the minimal acoustic energy in the presence of which he will say "I hear". Offhand it would not appear difficult to establish this value, but complications arise when we examine the concept of the threshold and the measurement procedure in more detail. The naive concept of the threshold is essentially the following: There exists a value I_t for any acoustic stimulus, such as a pure tone, that separates stimuli into

two classes. Those stimuli whose intensity* is less than I_t will never evoke a response, while those whose intensity is greater than I_t will always (under carefully defined "normal conditions") evoke a response.

The only problem is to determine I_t. Even a little preliminary experimentation shows us that events are not so nicely categorized. To be sure, there are values of the stimulus to which our subject hardly ever responds and others to which he practically always responds, (that is, unless he is asleep or daydreaming or otherwise "not paying attention"). But then, there are stimulus intensities to which he responds most of the time and others to which he responds perhaps only 30 per cent or 50 per cent of the time. In other words, there is a zone of uncertainty that surrounds I_t. The organism is variable and does not always behave exactly the same way when confronted with a stimulus which, according to our measuring instruments, is the same. This is not a serious difficulty if we are prepared to apply a little statistics. Let us determine the so-called psychometric curve that relates relative frequency of response to stimulus intensity, and let us define I_t as the intensity of the stimulus to which the subject responds 50 per cent of the time. We understand, then, that the absolute threshold is not a fixed point on the stimulus scale. A single value representing the absolute threshold must necessarily be a statistical quantity.

The problem that remains is the measurement of I_t with a microphone 13/. But where are we to put that microphone? In other words, where and how do we propose to measure the stimulus? To make a rather involved story relatively simple, let us say that we have several methods of measuring stimulus intensity. (i.e., the sound pressure that specifies the strength of the stimulation). We can measure the sound field as it exists in the absence of the subject and relate the subject's "I hear" to that stimulus value. Alternatively we can measure the actual sound pressure at the eardrum by means of a small probe microphone** and can consider this last look

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* Stimulus intensity is here defined as a generic term that relates to the strength of the stimulus; whenever we actually make measurements we specify the sound pressure level.

** The probe microphone sould not by the mere fact of its presence interfere appreciably with what you want to measure. This may not be such an easy matter, especially at high frequencies.

at the acoustic disturbance before it enters the organism as our effective stimulus. Both methods have been used. The first one goes under the name of minimum audible field (MAF) and the second one by the name of minimum audible pressure (MAP). Obviously threshold curves plotted in terms of MAF and MAP do not look quite the same.

Especially at the higher frequencies, there is a good deal of discrepancy between the two sets of curves since it is at those frequencies that diffraction effects around the head and resonance effects in the outer ear play their greatest role. The outer ear up to the eardrum acts like a small resonator at frequencies for which the wavelength is an appropriate multiple of the distance to the eardrum. Investigations dealing with these diffraction and resonance effects have brought MAP and MAF values for thresholds into reasonably close agreement 14,15/, except for a mysterious difference of about 6 db. This difference is particularly noticeable at low frequencies, and to explain it has so far taxed the ingenuity of many an investigator 16, 17, 18/.

Now that we have seen how I_t can be specified, are our troubles over? Not quite. We still have to settle upon an experimental method for determining I_t. Are we going to give our subject an oscillator, an earphone, and an attenuator and tell him: "Tell us the minimal setting of this dial at which you can hear a tone of 1000 cps"? Or, are we going to have him sit down in a chair and raise his finger every time he hears a tone while we manipulate the intensity of the stimulus up or down? Even though the actual techniques of measurement of a stimulus may contribute to the variability of the threshold, it is our suspicion that a good deal of the disagreement on threshold values between experimenters in the United States and in Europe, for instance, may be due to differences in the psychophysical method that is used to determine the thresholds. This may seem strange until we reflect upon the fact that even accurately calibrated thermometers will indicate different temperatures at points intermediate between the calibration points. We might even be able to show discrepancies if we use a single rod of copper and if we once measure the temperature on the basis of change in length of the rod and another time on the basis of a change in the electrical resistance. True enough, the discrepancies would be rather small and we would only be able to bring them out if we had a precise way of measuring temperature. However, this whole discussion emphasizes a fact (of which anybody who has dealt with microphones is quite aware), that data in psycho-acoustics, like

results in the physical sciences, are meaningful only if the method by means of which the results are obtained is specified.

In the section that deals with audiometry (Sec. 16.3)is a further discussion of some of the problems of how one measures the absolute threshold of hearing in an industrial or military situation in contrast to a laboratory situation. [For a detailed discussion of psychophysical methods used to measure thresholds, see I. J. Hirsh, The Measurement of Hearing 19/].

Let us now turn to the problem of man's "dynamic range". Figure 16.1 shows that under optimum conditions, we are able to detect a sound with an intensity of roughly 10^{-16} watts/sq cm. This is better than the "thresholds" of various high quality microphones. Various calculations have shown that a further increase in man's sensitivity would make it almost possible for him to detect the noise produced by the Brownian motion of the molecules in the air at normal temperatures. Experimental evidence tells us that the amplitude of vibration of the eardrum near man's lowest threshold is of the order of 10^{-10}cm, or about one-hundredth of the diameter of a hydrogen atom.

A question that we might legitimately ask is "How far above the absolute threshold do we have to go before man will experience pain?" We do not have any completely satisfactory data on the subject, but the best available evidence indicates that the range between the lowest absolute threshold and the threshold of pain is about 140 db. That is quite a respectable performance, if you compare it with the performance of any single physical instrument.

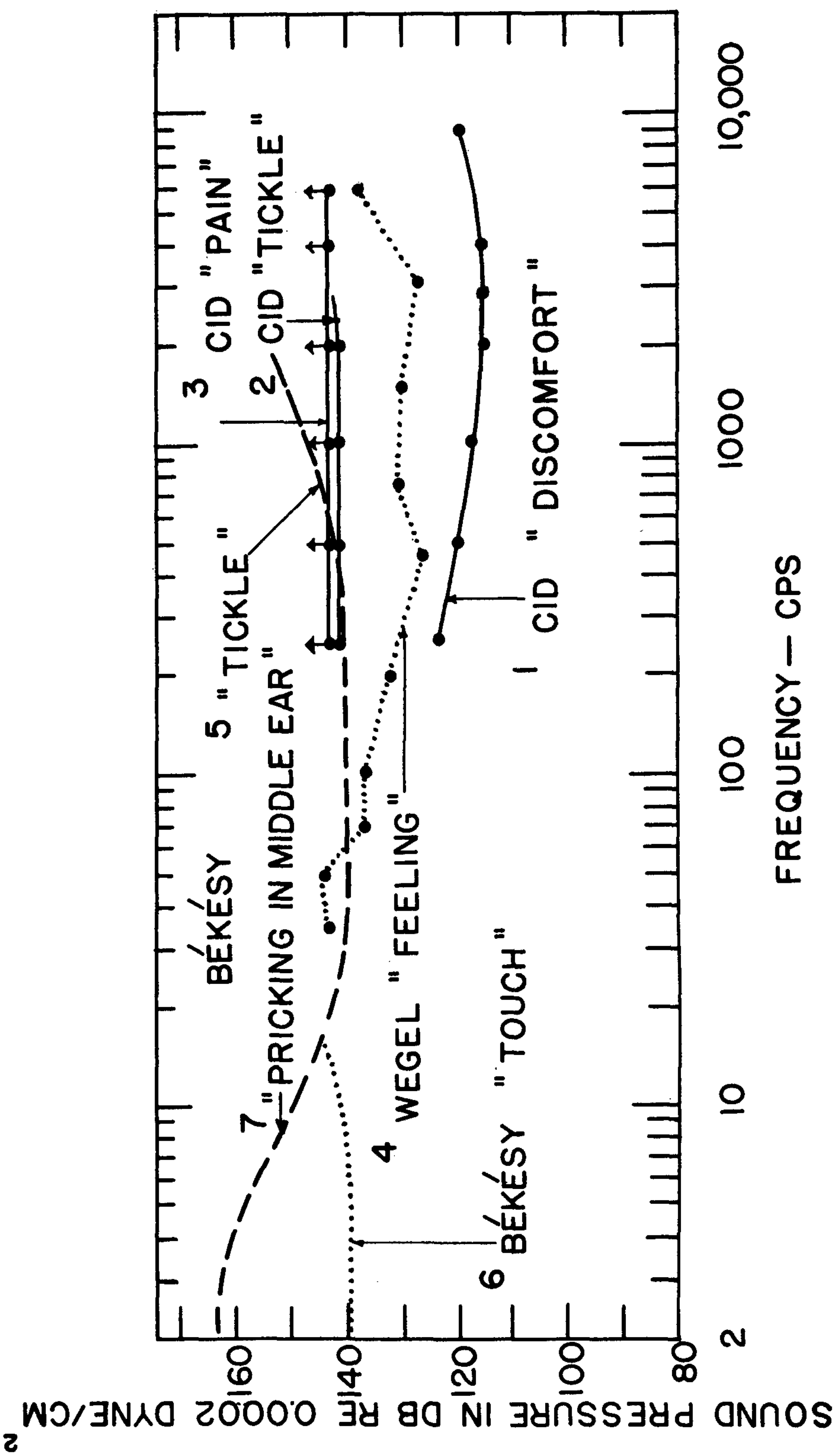
We have no intention of disparaging the data that have been collected on so-called tolerance thresholds, but there are some obvious difficulties involved in such a research project. First of all, there are certain semantic obstacles to be overcome. The older literature talked about thresholds of feeling or of tickle; the most recent investigation (Silverman 20/) attempted to establish three different contours; Silverman called them, in order, threshold of discomfort, threshold of tickle, and threshold of pain. The subjects were instructed in the meaning of these words, but as the investigation wore on, their standards shifted upwards in intensity. It is, of course, difficult to tell if this shift should be attributed to an accommodation process in the physiological

mechanism or to a psychologically different interpretation of such words as discomfort and pain. Before the investigation had terminated, the maximum sound pressure level that the earphones could produce was found to be too low to establish the ultimate thresholds of tickle and pain. All we can say is that for pure tones these ultimate values must lie above 142 db re 0.0002 dyne/cm^2. The tolerance thresholds for speech 20/ lie at 130 db (discomfort), 135 db (tickle) and above 139 db (pain).

We still do not know what the values would be if the stimuli had not been presented by earphone, but if the subject's head had been placed in a homogeneous sound field. It may also be worthwhile to point out that the sounds presented to the subjects were continuous. The intensity was increased in steps of 2 db every 1.5 seconds between 100 and 130 db, and in 1 db steps above 130 db. This procedure avoided some of the disagreeable complications that might have accompanied the sudden onset of a high intensity stimulus. It is, however, almost certain that the tolerance thresholds for sudden onset of stimuli would lie considerably below those shown on Fig. 16.2. Such thresholds may be influenced not only by a startle reaction, but also by the fact that it takes a time interval of the order of 1/100 sec. for the protective action of the middle ear muscles to take effect.

Figure 16.2

These curves show various determinations of tolerance thresholds for pure tones. Curves 1, 2 and 3 were reported by Silverman 20/ at the Central Institute for the Deaf (CID), in St. Louis. Curve 1 shows the intensity level at which, after an extended period of getting used to intense acoustic stimulation, the listeners reported "discomfort", and Curve 2 marks the onset of "a tickling sensation" The limit of the earphones was exceeded before some of the experienced listeners complained of "pain" (Curve 3). Curve 4 is the "threshold of feeling" obtained by Wegel 21/, and Curve 5 is Békésy's 3/ threshold of tickle. Békésy found that at frequencies below 15 cps his listeners could report consistently in terms of two criteria. Curves 6 and 7, labeled "touch" and "pricking in middle ear" show the central tendencies of the judgments. (After J.C.R. Licklider 9/).



3 CID "PAIN"
2 CID "TICKLE"
5 "TICKLE"
BÉKÉSY
7 "PRICKING IN MIDDLE EAR"
4 WEGEL "FEELING"
6 BÉKÉSY "TOUCH"
1 CID "DISCOMFORT"
2
10
100
1000
10,000
FREQUENCY — CPS
80
100
120
140
160
SOUND PRESSURE IN DB RE 0.0002 DYNE/CM²

Effects of Age on Threshold. The auditory thresholds discussed above were usually determined for young listeners who had had experience in auditory tests in the laboratory. Audiometric studies have shown, however, that there is a progressive increase in the threshold of hearing as a function of age. Since the evidence on effects of age has been collected in audiometric studies rather than in the laboratory, a discussion of this aspect of auditory thresholds is included in Section 16.3 on audiometry.

Differential Thresholds. Absolute thresholds and thresholds of tolerance are not the only thresholds we can determine. We may wish to determine whether a listener can distinguish stimulus A from stimulus B. The question we ask him may take various forms. We can ask him if A and B sound similar in every respect or if the stimuli sound different in any respect. We can then make our questions concerning differences more specific by asking, for instance, if A sounds higher or lower than B. If we were to use pure tone stimuli we could make tone A differ from tone B either in frequency or in intensity or both. We expect to get from the listener responses that will yield a statistical answer to the question of how small a change in the stimulus he can detect with a certain reliability. These so-called differential thresholds (or thresholds of detectability of a change in stimulus dimensions or characteristics) are important since they are related to the listener's ability to discriminate one signal from another; and information is usually conveyed by a set of changing signals.

There are a great number of different ways in which differential thresholds can be determined. We assume that we can measure stimulus intensity and frequency with sufficient accuracy and that we have at our disposal an infinite number of ways in which we can go from stimulus A to stimulus B. We could, for instance, attempt to modulate the amplitude of pure tones sinusoidally or by means of a square wave, or by means of a triangular wave, etc. Next we could vary the psychophysical method that we use to determine the just noticeable differences*. The value that we obtain for a JND will vary with the way in which we present the stimuli and

* Differential thresholds are also called difference limens (DL's), just noticeable differences, just not noticeable differences, etc.; just noticeable differences are abbreviated as JND.

with the psychophysical method. It will also depend upon the size of the stimulus ensemble and the number of alternative responses a listener is allowed to make. The size of the JND will not be independent of the time we give our listener to arrive at a determination of his discriminative capacity. Recently certain authors have reported "learning processes" 22,23,24/ in this connection that seem to continue for years. It should be fairly clear, therefore, that there is not just one value for a given just noticeable difference (in the literature) but there are quite a few.

The question is often raised that the only important figure must be the one that describes the organism's ultimate capacity. Discrimination of some acoustic signals, like speech, is always performed in a certain time span and under certain conditions of interfering noise. Since our main concern is with the effects of noise upon man's auditory performance, we shall want to measure the JND's in a certain way. We may wish to compare JND's obtained under certain standard conditions with JND's obtained in the presence of a prescribed amount of noise or after exposure to a specified amount of noise.

Figure 16.3 shows how the most widely accepted values for difference thresholds in intensity behave for different frequencies and for different sensation levels. We note that the just noticeable difference in sound pressure level decreases from about 3 db in the vicinity of the absolute threshold to about 0.25 db at sensation levels of about 60 db*. This should not be interpreted to mean that a man could correctly identify something of the order of 250 intensities for a pure tone of a particular frequency.** It is one task for a man to judge, most of the time, that a 1000 cps tone of 60 db sound pressure level is louder than a tone of 59.5 db sound pressure level. It is an entirely different task for a man to recognize from perhaps 250 different tones (all of them 1000 cps but of different sound pressure

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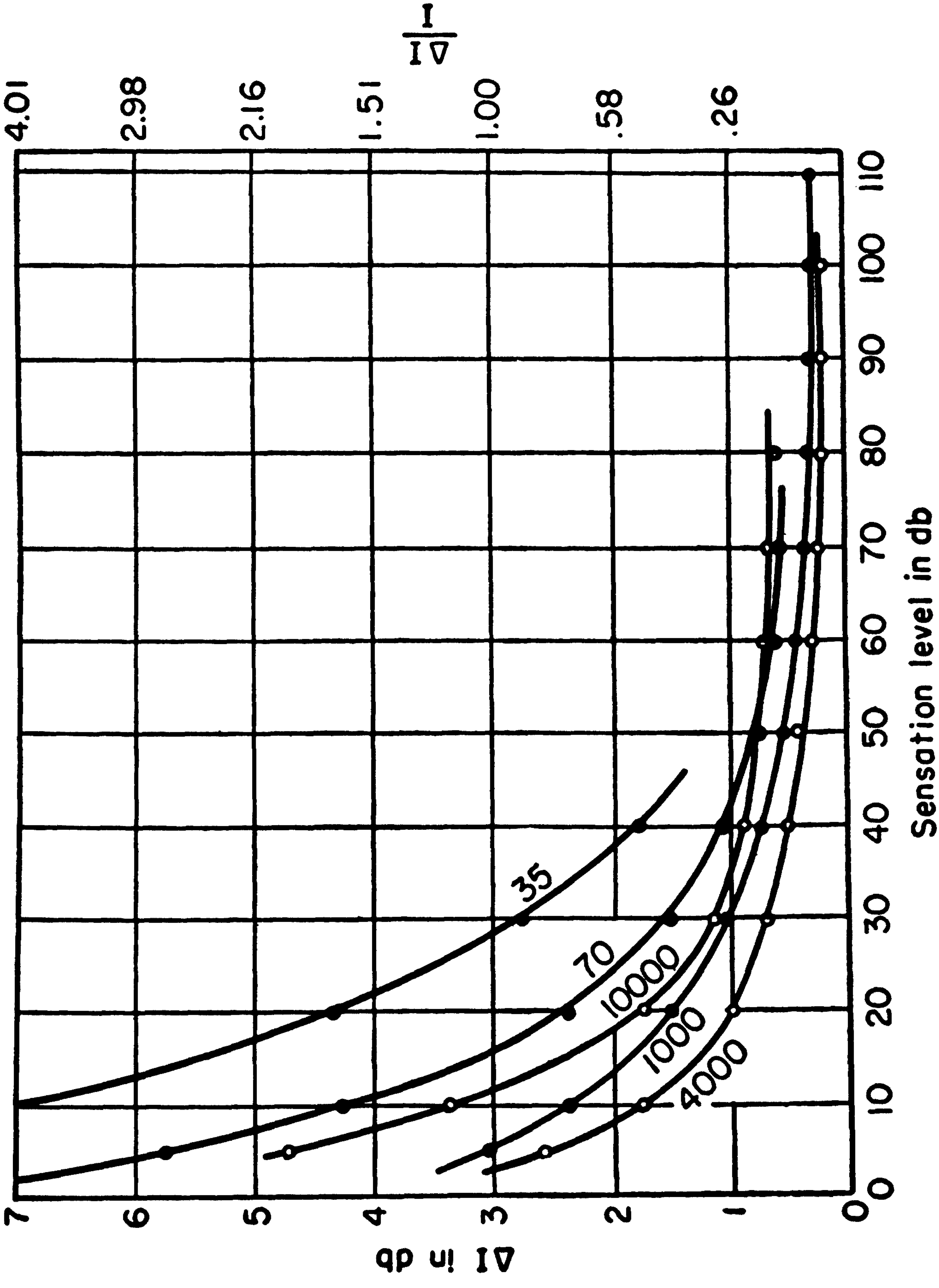
* For a definition of sensation level, see Chapter 15.

** We arrive at the figure 250 by dividing the auditory range (about 125 db) by the average JND in sound pressure level (about 0.5 db).



$\frac{\Delta I}{I}$
4.01
2.98
2.16
1.51
1.00
.58
.26
35
70
10000
1000
4000
0
10
20
30
40
50
60
70
80
90
100
110
Sensation level in db
7
6
5
4
3
2
1
0
ΔI in db

levels spaced one-half db apart) which one is labeled 59.5 db and which one is labeled 60 db sound pressure level.

Riesz's data are by no means beyond dispute; but they represent the most comprehensive set of measurements attempted so far. They were obtained monaurally with the help of a special distortion-free earphone and with the intensity of the stimulus tone varying in a sinusoidal fashion. For a discussion of some of the factors involved in determining a DL in intensity see Stevens and Davis 26/. For results that are not in agreement with Riesz's see G. V. Békésy 27/ and also Dimmick and Olson 28/.

So far we have dealt only with just noticeable differences in the intensity of pure tones. But as we have said before, pure tones do not occur very often in our natural environment and we would much rather know JND's for the intensity of bands of noise or of complex tones. We do not possess data on bands of noise but we have a careful investigation of sensitivity to changes in the intensity of white noise stimuli. Figure 16.4 shows Miller's 29/ data for two trained observers. Note that the JND is constant for sensation levels above 20 db. This is one of the instances in which the so-called Weber law* holds. Actually, the JND for white noise is somewhat smaller

* In 1834 Weber stated that the ratio of $\Delta I/I$ (where I is the stimulus intensity and ΔI the increment in stimulus intensity) is a constant for a just noticeable change in intensity. The Weber law has often been extended beyond the intensitive domain and has even been applied to frequency discrimination of pure tones. Under these circumstances authors have replotted the Shower-Biddulph data (see Figure 16.5) in an attempt to show that the $\Delta f/f$ ratio stayed relatively constant, at least for frequencies above 1000 cps.

Figure 16.3

Just noticeable difference ΔI in sound pressure level for pure tones reported by Riesz 25/. The parameter is the frequency of the pure tone. I represents the stimulus intensity. The value of $\Delta I/I$ is indicated at the right. The tendency of $\Delta I/I$ to be constant at high sensation levels should be noted.

than 0.5 db. This value is not too different from Riesz's average values for frequencies between 1000 and 4000 cps. Let us not overlook the fact that Riesz's and Miller's data were obtained for different observers and by different experimental techniques. We might emphasize the figure of 0.5 db since one finds so often in the literature the loose statement that the unit of 1 db was chosen because it represents the minimum change in intensity that can be discriminated.

The size of the JND for pure tones depends critically upon the sensation level of the stimulus. It depends considerably upon the time interval during which the intensity of the stimulus increases or decreases. This has been shown by Garner and Miller 30/ for short time intervals and by Lawrence et al 31/ for stimuli that last as long as 30 or even 60 seconds with a change in rate of up to 5 db/minute. Actually, intensity discrimination seems to be best for sounds of about 1 second duration. Frequency discrimination on the other hand does not seem to be too much affected by interposing silent intervals up to 10 seconds between the standard and the test tone 32/ while the JND for intensity increases with the length of the silent interval between standard and comparison tone.

Let us now turn to frequency discrimination. The data that are most commonly accepted were taken by Shower and Biddulph 33/ (see Fig. 16.5). Data on JND's in frequency for pure tones have recently been summarized in a manner that illustrates some of the variables that affect performance 24/ (Fig. 16.6). JND's in frequency pose essentially the same problem as JND's in intensity. We must distinguish between (1) ability to tell the difference between two stimuli presented in close succession and (2) ability to identify correctly one out of a large set of stimuli when presented in isolation. The former problem is a case of

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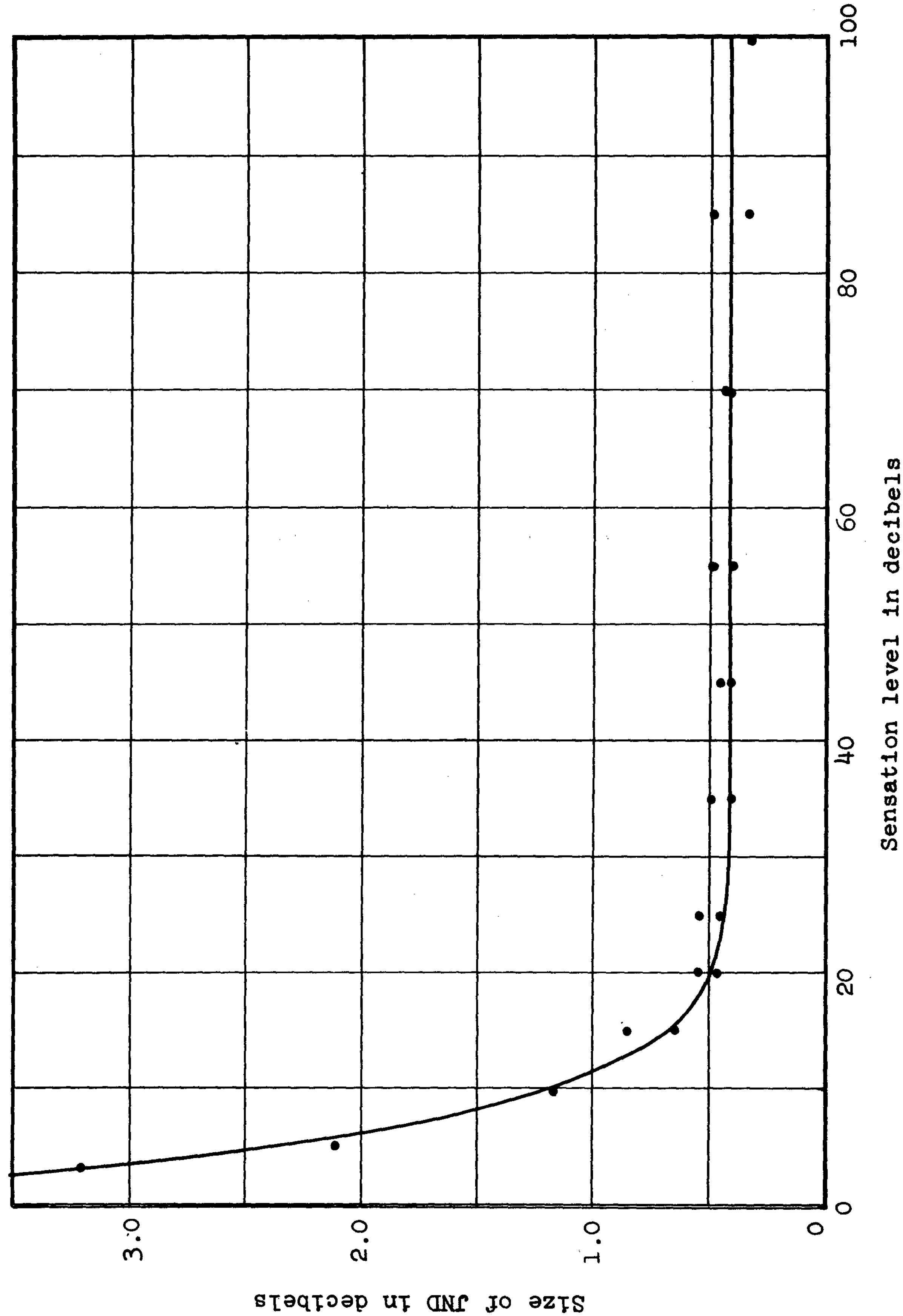
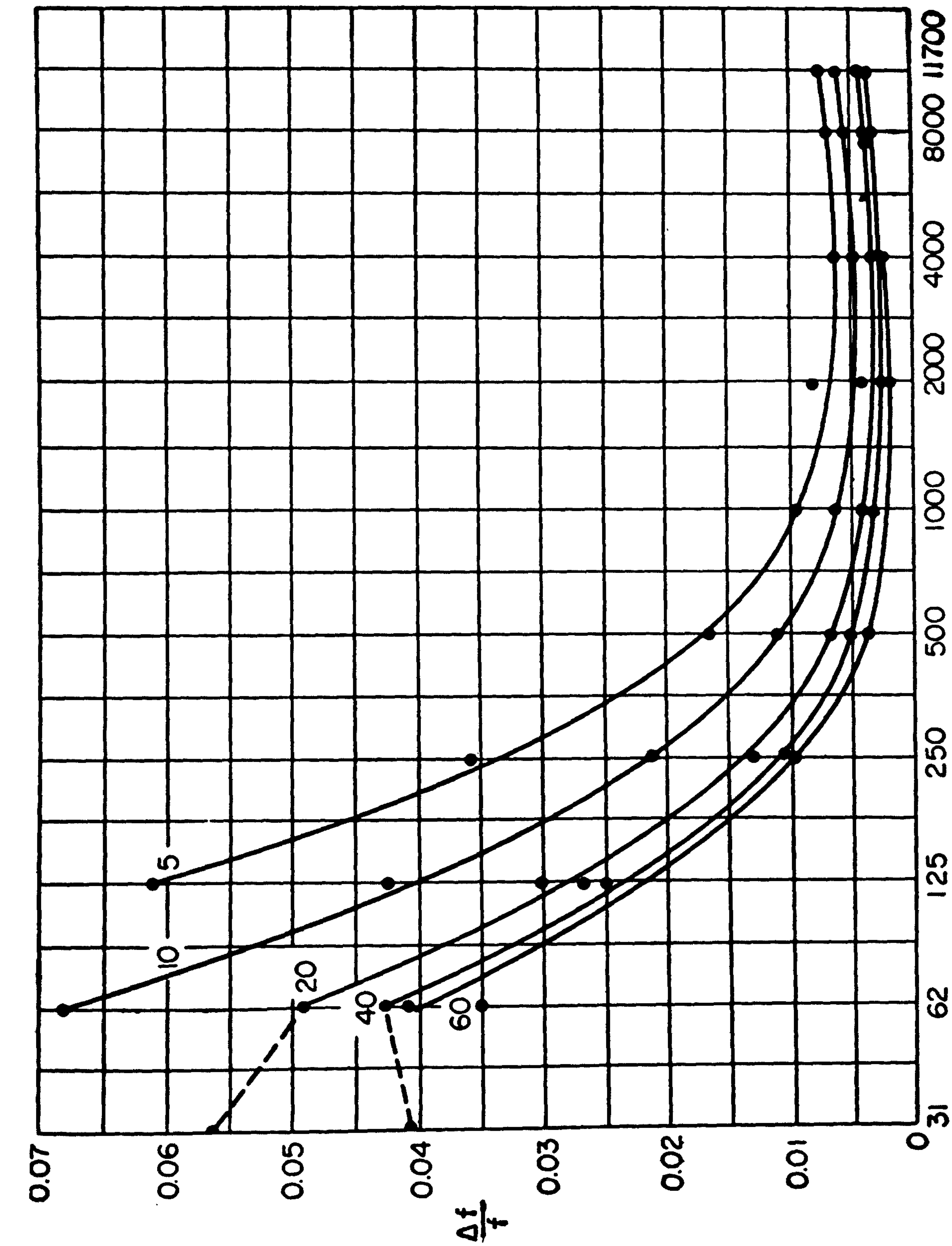
Figure 16.4

Just noticeable differences in sound pressure level for white noise in a 7000 cps band. Increments in intensity heard 50 percent of the time are plotted as a function of the intensity of the noise in decibels above the threshold of hearing. The Weber fraction $\Delta I/I$ remains essentially constant above the 20 db sensation level. (After Miller 29/)


Sensation level in decibels
0
20
40
60
80
100
Size of JND in decibels
0
1.0
2.0
3.0


0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
$\frac{\Delta f}{f}$
31
62
125
250
500
1000
2000
4000
8000
11700
Frequency
5
10
20
40
60

relative discrimination, while the latter involves absolute identification. Thus the fact that we are able to identify a 1003 cps tone from a 1000 cps tone does not mean that we can simply divide the frequency range in cps by the average JND to find out how many different pure tones an average subject can correctly identify. One recent study using frequencies between 100 and 8000 cps showed that average listeners gave results that could be considered equivalent to perfect identification among five tones only 34/. There are, of course, sizeable individual differences in terms of more basic concepts. Though we have no complete investigation of the problem, there is evidence that permits us to estimate that people with so-called "absolute pitch" have apparently learned to identify correctly a number of tones perhaps 10 to 20 times larger than ordinary subjects. The question still remains open as to whether subjects are able to do better because they have some verbal labels to pin upon the stimuli, or because they are "superior discriminators" in every respect. The evidence on this latter point would seem to indicate that a person having "absolute pitch" is not much better than the run-of-the-mill laboratory subject, when it comes to the identification of loudness. (W. D. Ward, Personal Communication).

In the above discussion we have considered discriminations of a relatively simple type involving changes of intensity or frequency only. A more complex type of discrimination was investigated by Karlin 35/ who measured the ability of subjects to detect small changes in a noise spectrum. The chief characteristics investigated were the frequency and intensity of noises.

The stimuli were obtained by passing white noise, in which all components were of uniform intensity level, through a band-pass filter. Variations in the pitch of the noise were achieved

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Figure 16.5

Just noticeable differences in frequency for pure tones, as obtained by Shower and Biddulph 33/. The ordinate is the ratio of the JND Δf to the frequency f, and the parameter is the sensation level of the tone in dbs. The frequency was varied in an approximately sinusoidal fashion at about 2 cps.

by varying the sharpness of the cutoff attenuating characteristics of the band-pass filter; for example, higher pitch resulted from sharpening the high-pass attenuation characteristic, and flattening the low-pass characteristic. Variations in loudness were achieved by raising and lowering the overall intensity of the noise. In both tests a standard noise of two seconds' duration was presented first, followed instantaneously by the variable noise, also of two seconds' duration.

The changes in spectrum shape that were just discriminable by Karlin's subjects in his pitch test are shown in Fig. 16.7. The curves marked "lower" and higher" were judged to be lower and higher in 75% of the subjects' votes. In the test of loudness discrimination, the DL for a band of noise from 500 to 2000 cps was about 0.4 db, indicating fair agreement with Miller's data.

Karlin reported that the pitch and loudness test appear to measure significant abilities which are largely independent of each other. Neither could be used to predict performance on the other. He also showed that there is little overlap between the abilities involved in the noise tests and those in corresponding tests employing pure tones instead of noises.

Further experiments on differential thresholds for complex tones have been reported by K. N. Stevens 36/. He measured DL's in frequency and in bandwidth for damped waves and for noise shaped by simple tuned circuits. In general, his

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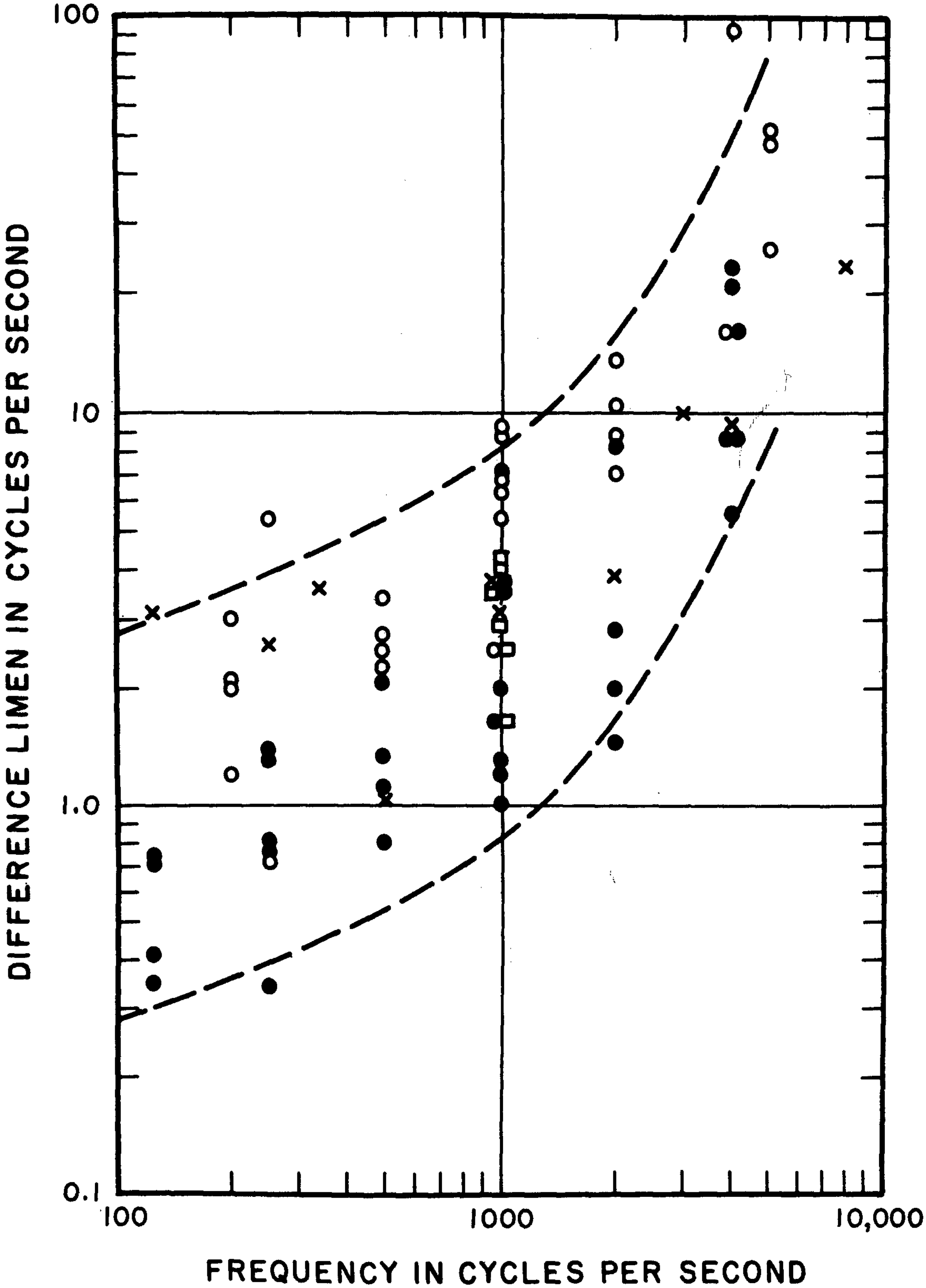
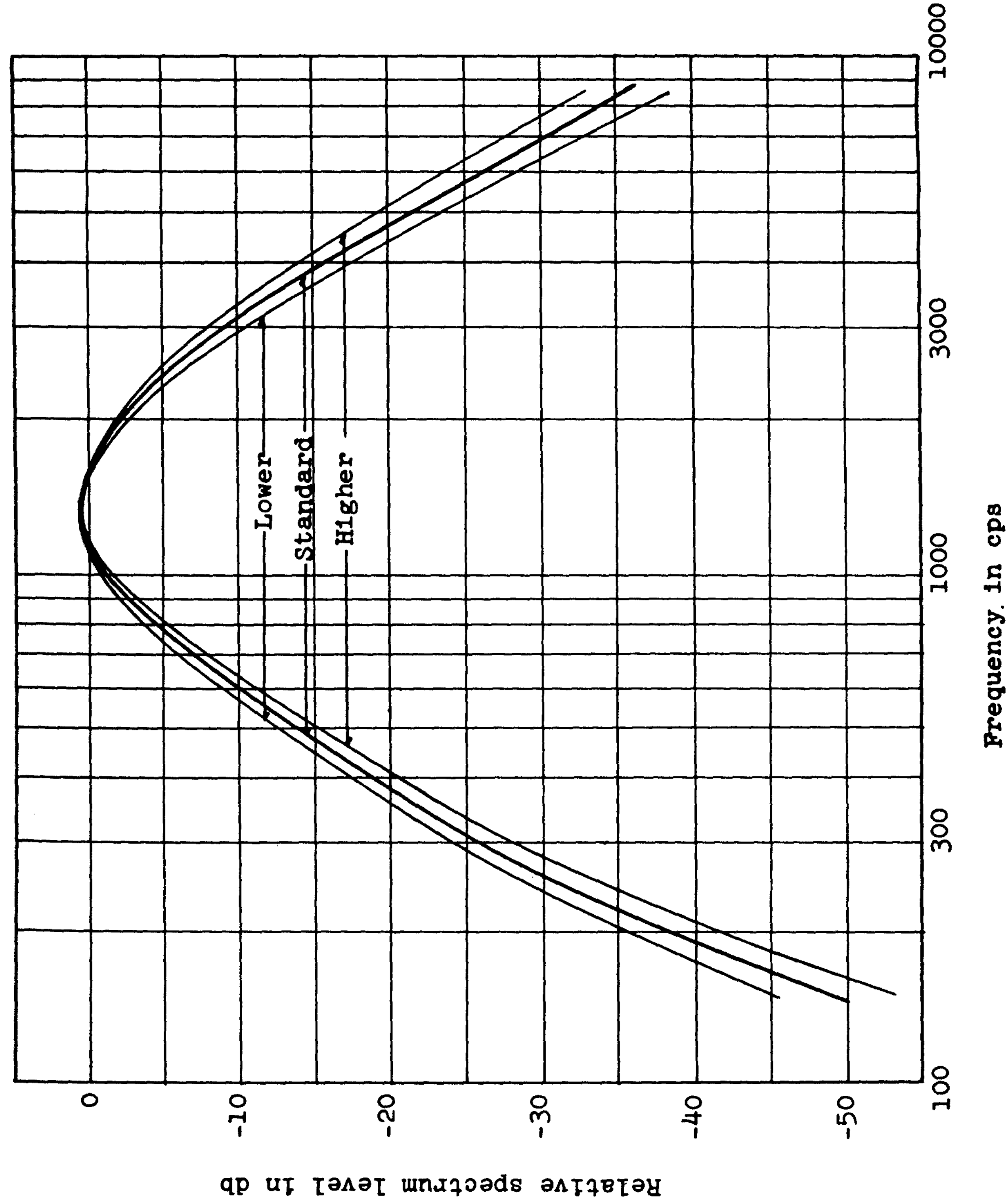
Figure 16.6

Data on pitch discrimination reported by several investigators are shown in a single graph. Data obtained by different psychophysical procedures are shown by different kinds of points on the graph. The closed circles represent data taken by the AX method, and the open circles represent DL's from the ABX method. Data obtained by a frequency modulation procedure are shown by X's, and data from the quantal method by squares. Almost all data lie within the dashed lines, which indicate a spread of one decade. (See Rosenblith and Stevens 24/ for a discussion of the AX and ABX methods).


100
10
1.0
0.1
100
1000
10,000
DIFFERENCE LIMEN IN CYCLES PER SECOND
FREQUENCY IN CYCLES PER SECOND



Lower
Standard
Higher
Frequency in cps
100
300
1000
3000
10000
0
-10
-20
-30
-40
-50
Relative spectrum level in db

results indicate that as the bandwidth of the stimulus is broadened, the discrimination of changes in bandwidth and in frequency becomes less acute.

We could, of course, determine JND/s for a great number of other variables such as direction or distance of a sound source. We could investigate the way in which these thresholds differ when we manipulate the duration (and thus alter to some extent the spectrum) of the sound in question. We could observe how a JND differs when the listening is done monaurally or binaurally. We could choose a rather complex stimulus like a musical tone and test for the absence or presence of certain harmonics or distortions. While these data would be of considerable interest from a psycho-acoustic viewpoint, they do not concern us sufficiently here to go into details.

Loudness. We have now seen that in trying to understand man's responses to acoustic stimuli, we have had to measure such quantities as absolute thresholds, tolerance thresholds, and finally differential thresholds or just noticeable differences. These characteristic values permit us to some extent to evaluate man's discriminative capacities in the domain of hearing. However, we may want to know more than how weak a stimulus man can detect or how strong a stimulus man can stand. We may also want to know what relations exist among the psychological responses evoked by various loud or annoying noises whose physical characteristics we are able to measure. For example, we might wonder if B sounds as

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Figure 16.7

Just noticeable differences in the spectrum of a noise as measured by Karlin 35/. The curves marked "higher" and "lower" represent the noise spectra that are correctly differentiated from the standard 75 per cent of the time.

loud as A. More generally, we may ask how the loudness* of a sound changes as we change its intensity. We should thus like to be able to obtain psychophysical scales that will relate man's judgment of the loudness of a sound to its sound pressure level.

Most of our discussion in the present chapter has involved single frequency sounds or random stimuli such as thermal noise. Sounds of organized complexity, such as musical tones or speech sounds, are different in character; here multiple cues determine the response to the stimulus. These cues are not necessarily independent of each other, and hence are difficult to measure. This means that we should not expect simple psychophysical relations to hold for the loudness of such complex tones.

We understand that we can in general rate sounds from soft to loud. It seems fairly obvious that sounds become louder as their intensity is increased**. However, we have to take certain precautions if we want to establish a loudness scale of a sort where sound A having one unit of loudness

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* The American Standard Acoustical Terminology defines loudness as the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud. It also states that loudness depends primarily upon the sound pressure of the stimulus, but it also depends upon the frequency and wave form of the stimulus. While this definition involves the term 'sensation', it should be clear that we shall be concerned only with measurable human responses and their relations to physical characteristics.

** There are notable exceptions to this monotomic relation. The most striking exception occurs for high stimulus intensities at low frequencies (perhaps 20 cps and below; see Békésy 37/). This behavior has been attributed to the fact that for the large displacements involved the ossicles vibrate in a different mode, in a manner that reduces the actual stimulus power delivered to the inner ear. (See Appendix 1).

will sound one-half as loud as sound B of two loudness units, and at the same time, twice as loud as sound C having one-half unit of loudness. The problem of establishing such a scale, known technically as a ratio scale 38/, is an intricate one. It is by no means certain that all the various methods that one can use in order to establish this scale will yield the same loudness scale. This should not surprise us too much since similar difficulties (though most of the time not of the same magnitude) are encountered whenever a quantity is measured by several methods.

Whenever we use natural numbers like those we derive from counting procedures we have to specify their meaning rather carefully. When we see in an advertisement that substance A is three times as effective as substance B, we do not necessarily know how effectiveness has been defined. The writer of the advertisement may have asked a group of people if substance A is more effective than substance B and have found that 75 percent of the population believe substance A is more effective, while only 25 percent believe that substance B is more effective. This does not, of course, mean that substance A is three times as effective as substance B if we attach some other criterion to the meaning of the word "effectiveness".

Let us, therefore, proceed step-by-step. First let us see if we can establish equal loudness relations for pure tones. In order to do this let us ask the following question. If we raise the sound pressure level of pure tones by 10 db above the absolute threshold, will these tones be judged equally loud? Will the same be true if we raise the sound pressure level for different frequencies by 80 db? Such an experiment assumes implicitly that all tones are equally loud at threshold. This is merely an assumption but an eminently reasonable one. As long as we add just a few decibels to threshold intensities, we preserve our equal loudness relationship fairly well, with the possible exception of the very low frequencies. However, if we continue to add an equal number of decibels at all frequencies, we find that the loudness of pure tones in the low and high frequency regions increases more rapidly than the loudness of tones in the range between 1000 and 4000 cps. As the equal loudness contours in Fig. 16.8 show, a 1000 cps tone

having a sensation level* of 70 db is judged equally loud to a 100 cps tone of approximately 40 db sensation level (or 78 db). However, a 1000 cps tone having a sound pressure level of 20 db, is judged as loud as a 100 cps tone having a sound pressure level of 51 db. An acceptable generalization for equal loudness contours might, therefore, be formulated as follows: near the absolute threshold, equal loudness contours follow rather closely the contours of equal sound pressure level. Equal loudness contours measured in terms of (1) sound pressure at the eardrum, and (2) sound pressure in a free field before insertion of the head are shown in Figs. 16.8 and 16.9.

From these equal loudness contours we can already draw the conclusion that in order to judge the loudness of a tone it is not enough to know merely its stimulus intensity, but we must know its frequency also. Historically, the next concept that was introduced in the development of a loudness scale was that of loudness level. Its definition states that the loudness level (in phons) of a sound is numerically equal to the sound pressure level in decibels (relative to 0.0002 dyne/cm^2) of a 1000 cps tone that is judged by the listeners to be equally loud. This concept of loudness level permits us, if we are concerned only with the loudness of a tone, to ignore its frequency. All that is necessary is to compare its loudness with that of a 1000 cps tone; if we can measure the SPL of the 1000 cps tone we can then state the loudness level of the tone in phons.

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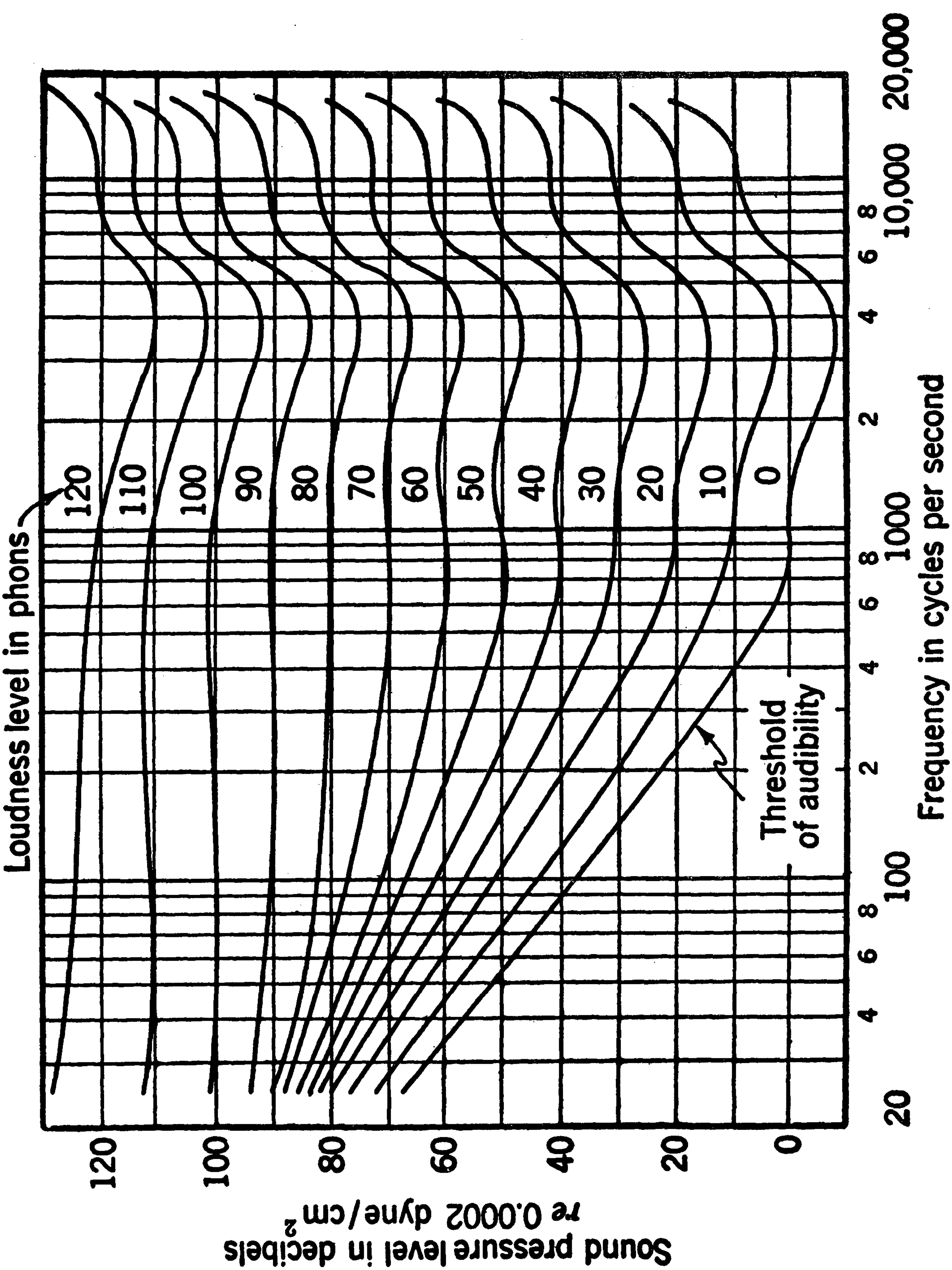
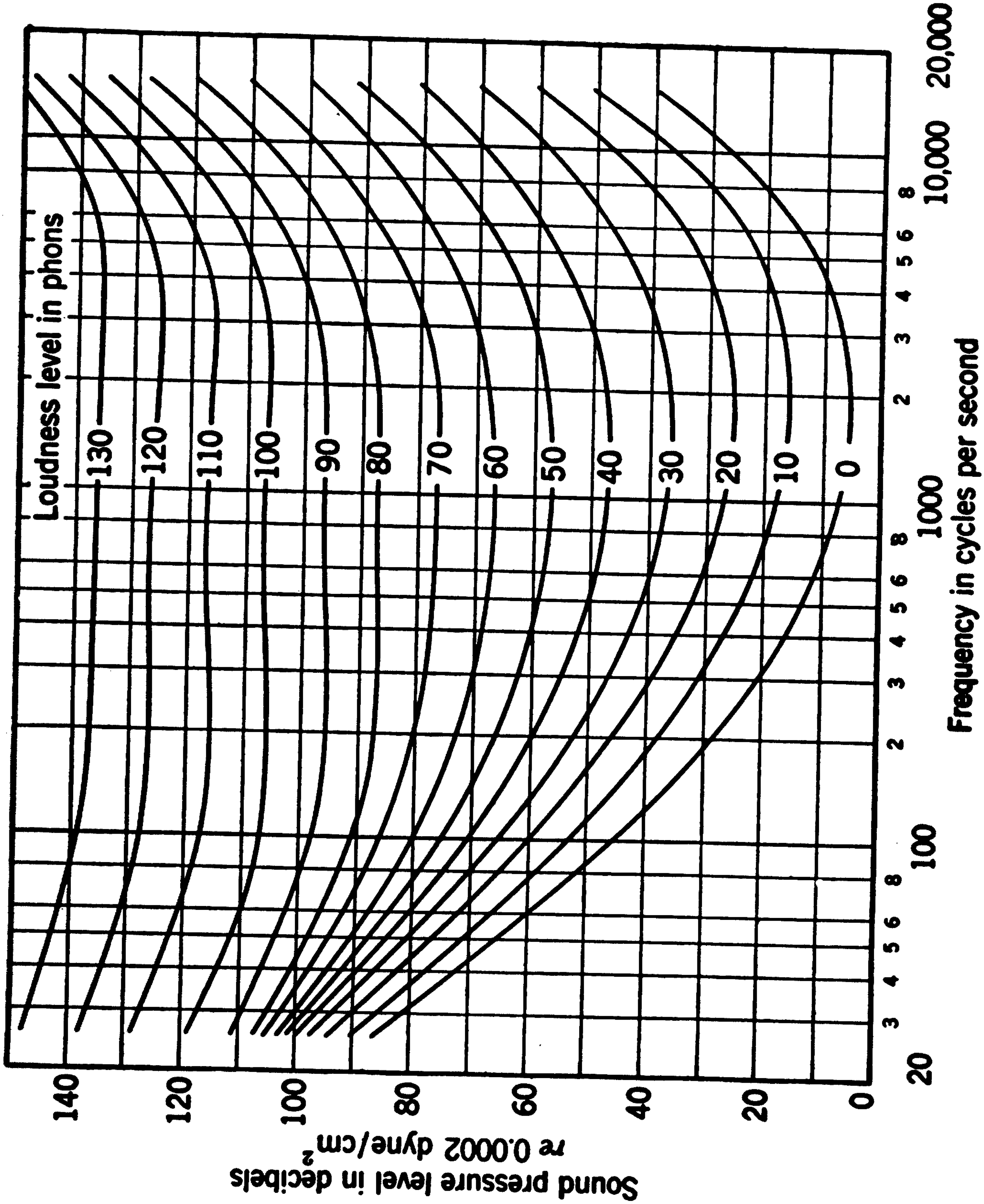
* The sensation level (level above threshold) of a sound is the pressure level of the sound in decibels above its threshold of audibility for the individual observer.

Figure 16.8

Contours of equal loudness. The sound pressure levels were measured in a free-field before entry of the subject. (After Fletcher 39/).


Loudness level in phons
120
110
100
90
80
70
60
50
40
30
20
10
0
Threshold of audibility
Frequency in cycles per second
20
4
6
8
100
2
4
6
8
1000
2
4
6
8
10,000
20,000
Sound pressure level in decibels
re 0.0002 dyne/cm²
120
100
80
60
40
20
0


Loudness level in phons
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Frequency in cycles per second
20
100
1000
10,000
20,000
Sound pressure level in decibels
re 0.0002 dyne/cm^2
0
20
40
60
80
100
120
140

We have now made several steps toward a genuine loudness scale for pure tones. Next we need a relation between loudness level and loudness, because the loudness level of a tone does not yet tell us which tone is twice as loud as the tone we are interested in. In particular, a tone having a loudness level of 20 phons is by no means twice as loud as a tone whose loudness level is 10 phons. A relation between loudness and loudness level was obtained experimentally and a unit of loudness was chosen to label the ordinate (See Fig. 16.10). The loudness of our reference tone of 1000 cps at 40 db SPL is called one sone (or 1000 millisones). We now see that a tone whose loudness level is only 20 phons has a loudness of 90 millisones while a tone whose loudness level is 60 phons has a loudness of 5 sones. One hundred phons corresponds to a loudness of 100 sones.

Let us not forget that the curve of loudness vs. stimulus intensity (SPL) in db for various frequencies would not be unique. We have to realize that the loudness vs. intensity function is different for different frequencies. The single curve of Fig. 16.10 is the result of the use of the intermediary concept of loudness level, and in some sense demonstrates the usefulness of that particular concept.

Let us now consider the loudness of some stimuli more realistic than pure tones: white noise, speech, musical tones, factory noises, jet noises, etc. The loudness of these sounds could be evaluated by tedious psychophysical tests. We should like, however, to be able to estimate their loudness on the basis of physical measurements, utilizing the pure-tone loudness curve that has already been established. Some preliminary computational schemes for the loudness of such sounds have been suggested but we are not yet on really firm ground. Several investigators 39,41,42,43/ have been concerned with measurements of the loudness of complex tones; they found that the loudness of these complex tones can be predicted by adding the loudnesses (not the intensities!) of the several components. This procedure fails if there is too much "interaction" between the

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Figure 16.9

Contours of equal loudness. The sound pressure levels were measured at the eardrum, and an earphone was used to deliver the tone. (After Fletcher and Munson 40/, re-plotted by Stevens and Davis 26/).

separate components. It would lead us too far to go into detail concerning that interaction but it appears safe to assume that loudness addition will fail when we get into a region of mechanical nonlinearity (i.e., very intense stimuli). Loudness addition will also fail if the components of the complex stimulus lie sufficiently close in frequency so that they compete for the same physiological units.

Pollack 44, 45,46,47/ has recently obtained loudness judgments from several highly trained observers for such stimuli as white noise, bands of noise, interrupted noise, and speech. Equal loudness contours for bands of noise are shown in Fig. 16.11. On the basis of the present evidence it appears that as long as the sound is fairly continuous in character, and as long as certain other conditions are fulfilled, we can obtain reasonably consistent loudness judgments for these types of stimuli in laboratory situations. However, the accuracy and consistency of these judgments from highly trained observers is by no means such that we should expect to be able to make use of their loudness scale for complex stimuli in everyday situations.

Pollack obtained data in experiments in which the loudness of a white noise was judged directly. A comparison of these data with others derived from experiments involving loudness transformations between the noise and a 1000 cps tone pointed up considerable discrepancies. Let us quote an example: a white noise of 100 db SPL is judged directly to have a loudness of about 700 sones while its "derived" loudness barely exceeds 100 sones. Pollack points further to the fact that, while a given listener will yield repeatable results in equal loudness matches, differences among listeners may reach as much as 30 db.

Recently the whole concept of a unique loudness scale has been subjected to a searching critique by Garner 48/. In a series of experiments he has studied the extent to which listeners vary in making half-loudness judgments. He has

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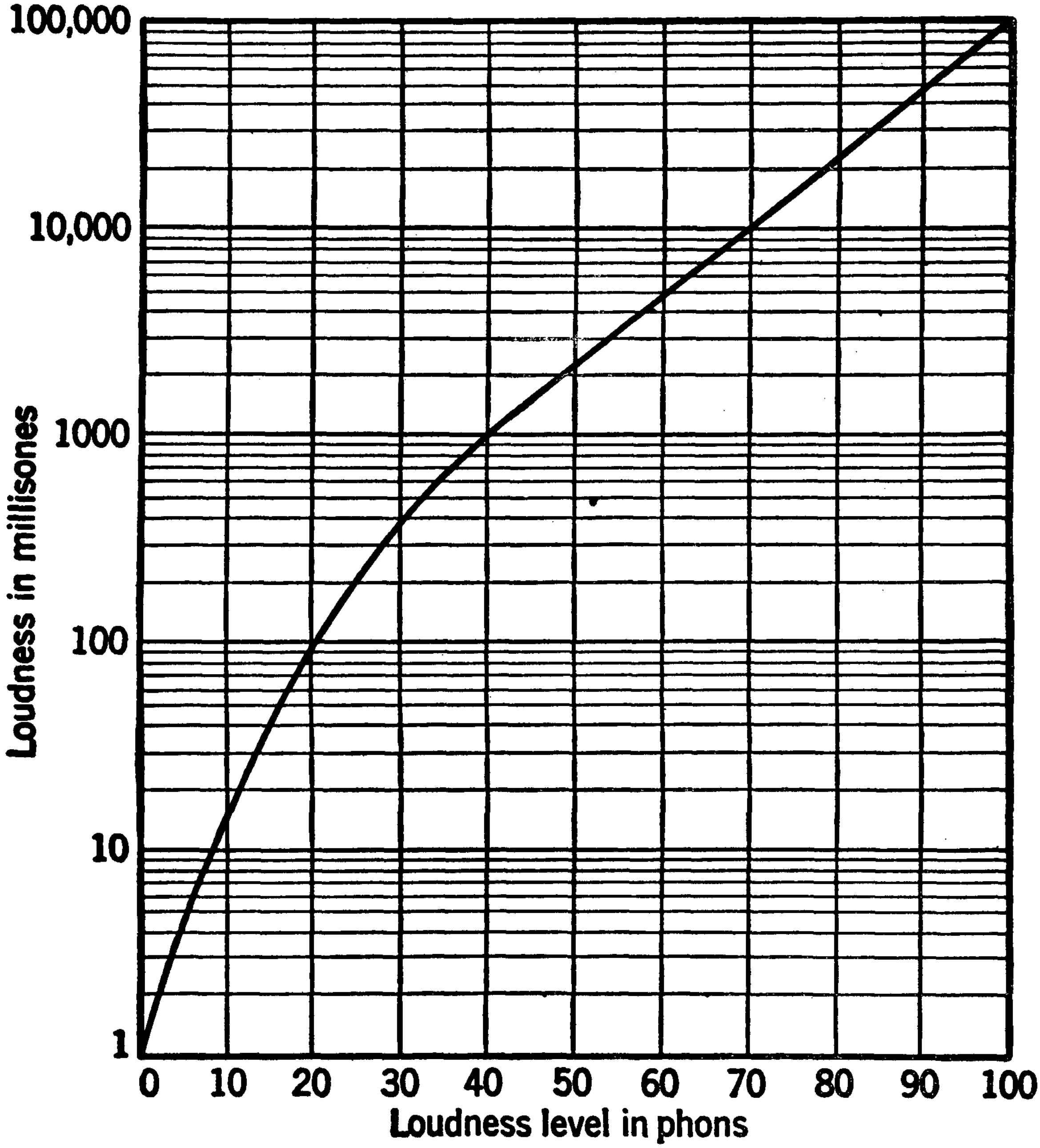
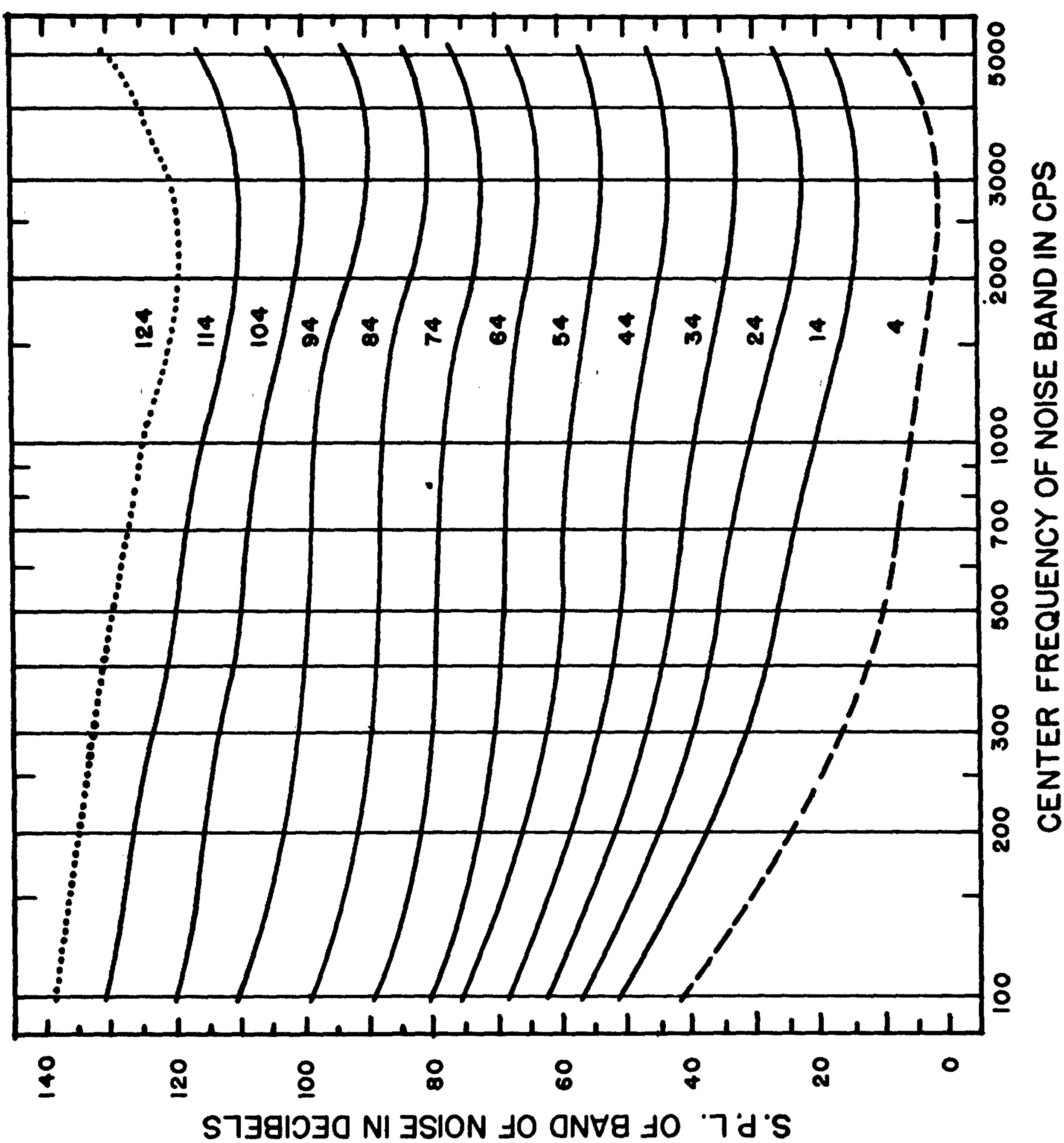
Figure 16.10

Loudness in sones as a function of loudness level in phons. Here the sounds are assumed to be presented to an uncovered ear. (After Fletcher and Munson 40/).


100,000
10,000
1000
100
10
1
Loudness in millisones
0 10 20 30 40 50 60 70 80 90 100
Loudness level in phons


S.P.L. OF BAND OF NOISE IN DECIBELS
140
120
100
80
60
40
20
0
CENTER FREQUENCY OF NOISE BAND IN CPS
100
200
300
500
700
1000
2000
3000
5000
124
114
104
94
84
74
64
54
44
34
24
14
4

furthermore, been concerned with the problem of whether listeners will generate the same loudness scale when the operation by means of which they generate the scale is fractionation, (as for example, half-loudness) or bisection (what tone lies halfway between tone A and tone B in loudness).

Pollack has also shown that if thermal noise is interrupted at rates between 2 and 10 seconds, one will then determine a loudness that is judged greater than when noise of the same level is presented in a continuous fashion. It would appear that under these circumstances, the temporal characteristics of the nervous system prevent the maintenance of a single monotonic relation between loudness and energy.

In spite of all these difficulties the last two decades have seen several attempts to calculate the loudness of sounds directly from their sound pressure spectra. Beranek et al 43/ discussed these attempts in a recent paper in the following manner: "In their classical work on loudness, Fletcher and Munson 40/ developed a method of calculation suitable for determining the loudness of complex tones from the frequency spectrum. The loudness of a continuous spectrum noise may be calculated by a procedure developed by Fletcher and Munson 41/ which requires a subjectively determined masking audiogram as starting data. Each of these methods is suitable only for the particular kind of noise for which it was developed, and each is somewhat cumbersome to use. Fletcher and Munson also outlined a procedure for calculating the masking audiogram of a continuous spectrum noise given its frequency spectrum 41/. They correctly restricted their method by the condition that

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Figure 16.11

Equal loudness contours for bands of noise (bandwidth about 250 to 300 mels) as a function of the center frequency of the noise band. The parameter is the loudness level, or the sound pressure level of an equally loud 1000 cps tone. Listening was monaural, and the sound pressure levels were measured just beneath the cushion of the earphone. (After Pollack 46/).

the intensity I does not change abruptly from one frequency region to another. When one attempts to use their method beyond this restriction, large discrepancies between calculated and subjectively determined loudness values can occur. For example, attempts to apply the Fletcher-Munson procedure to the calculation of the loudness of narrow bands of noise located at low frequencies leads to loudness levels which are lower than those subjectively determined by up to 25 phons."

Beranek and his co-authors expressed the opinion that " a simple objective procedure for determining the loudness of any type of noise with reasonable accuracy" would be of great value in engineering applications. On the basis of this evaluation of the situation and with the hope of providing a rational basis for a loudness meter they described an equivalent tone method for the calculation of the loudness of sounds. The main steps in this ingenious procedure are as follows:

"1. Divide the noise spectrum into bands of frequencies, each at least greater in width than a critical bandwidth for hearing, but not greater in width than about 600 mels. Bands between 300 and 600 mels in width seem best.

2. Determine the sound-pressure level in decibels for each band.

3. By means of the equal-loudness contours for pure tones, find the loudness level in phons for each band corresponding to the sound-pressure level of step 2 and the mean frequency of the band.

4. Using the relation between loudness and loudness level (Fig. 16.10) determine the loudness in sones contributed by each band.

5. Add the individual values of loudness to obtain the total loudness in sones."

Comparison of loudness values calculated by the equivalent tone method with experimental data obtained by Pollack 44,46/, Fletcher-Munson and others shows satisfactory agreement. Mintz and Tyzzer 49/ have used the equivalent tone method as a basis for developing a loudness chart for octave-bands of noise. However, a really extensive empirical test

of this method is still to come. In view of the above reported difficulties with a loudness scale for pure tones, one should not be too optimistic about the chances of developing a simple loudness meter. There is at least some reason for believing that loudness as an aspect of man's response to sound has been over-rated, otherwise the amount of variability in loudness judgments would be indicative of a rather serious situation.

In summary, we have seen that we are able, under certain restrictions, to set up psychophysical scales of loudness for pure tones and noises of a more or less continuous type, but that we must beware of extrapolating those scales for types of stimuli for which they have not been validated empirically. In view of all these findings, we are yet rather far from being able to build a loudness meter that will imitate the judgments of the average man over a realistic range of stimulus conditions. A further word of caution should be directed towards those who assume that loudness and annoyance are more or less synonymous (See Sections 17.3 and 18.4).

Pitch. Some of the readers may be rather surprised that up to this point we have talked very little about the sensation of pitch. Pitch perception is very often identified with hearing and most theories of hearing aim at explaining man's ability to discriminate pitch.

What is pitch? The American Standards Terminology defines it as "that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high, such as a musical scale." If we forget for the moment about the use of the term sensation, we could realize that the preoccupation with pitch stems largely from the period in which laboratory subjects were judging pure tone stimuli. A pitch scale, the mel scale, has been developed for pure tone stimuli and represents one of the best examples of a psychophysical scale.(See Fig. 16.12). Pitch is undoubtedly an important aspect of auditory perception and yet most attempts to quantify the pitch of complex sounds (resembling the sounds we encounter in nature, in everyday life, and even in the vicinity of noisy engines and machines) have been relatively unsuccessful. The pitch of complex sounds is often schizophrenic in its behavior. Recently, workers in this field have assigned at least two dimensions to the pitch of complex sounds 51,52,53/.

From the rather practical viewpoint that is ours here, there is not much concern for pitch judgments in the larger field of bio-acoustics. Pitch belongs more particularly to the sub-field of psycho-acoustics. There are three areas in which modified pitch perception might play a role in the phenomena with which we are concerned in this handbook.

There is, first of all, the observation that the pitch of a pure tone is not independent of stimulus intensity 54, 55,56/. However, this phenomenon has recently been shown to be so much affected by individual differences that we are not left with any particularly safe generalization. There is, secondly, the fact that the presence of bands of noise modifies somewhat the pitch of pure tones 57,58,59,60/. Again we find a great deal of variability and we are at present not inclined to believe that this pitch shift is particularly important from the viewpoint of auditory communication. From our point of view a most important effect upon pitch occurs in the neighborhood of frequency regions of severe hearing loss. Judgment of pitch is then often badly impaired and distorted, and tinnitus may interfere with pitch perception in a drastic manner. We shall return to this aspect when we consider the after-effects of severe noise exposures and at that time consider if there is a possible relation to faulty speech communication.

Localization of Sounds in Space. In addition to absolute and differential pitch functions and loudness functions, psychologists have quantified several other attributes of "auditory sensation" such as volume, brightness and density. However, there is little to make us take an interest in these

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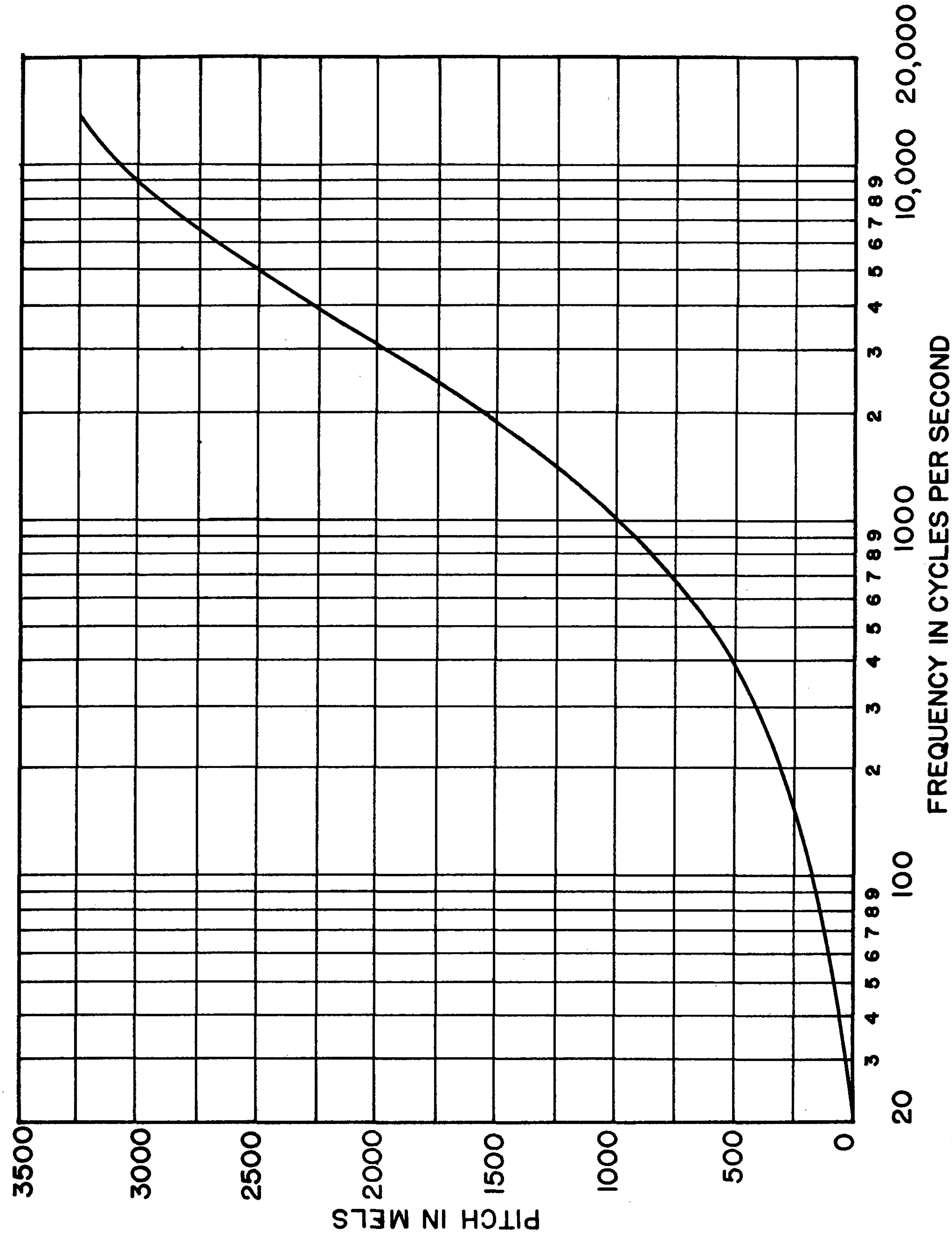
Figure 16.12

The pitch function. This curve shows how the perceived pitch of a tone (measured in mels) changes as a function of the frequency of the stimulus. This pitch function was determined at a loudness level of 60 phons. The mel scale was constructed by assigning arbitrarily the number 1000 to the pitch of a 1000 cps tone. The number 500 is assigned to the pitch of a tone that sounds half as high, etc. (After Stevens and Volkmann 50/).


FREQUENCY IN CYCLES PER SECOND
20
100
1000
10,000
20,000
PITCH IN MELS
0
500
1000
1500
2000
2500
3000
3500

attributes from the rather utilitarian viewpoint that has been ours. There is, however, one other function that ought to interest us: how do people localize sounds in space? Does the fact that man has two input channels (ears) help him in determining from which direction a particular sound arrives and also how far away from him the sound source is located? Is man helped by the fact that he can move his head?

Let us say at the outset that we know relatively little concerning the way in which distance is determined and must, therefore, limit ourselves to the problem of identifying the direction of a source of sound. The usefulness of this ability is hardly in dispute and the accuracy with which man seems normally to be able to do the job is rather startling (if we disregard certain confusions in symmetrical front and rear locations).

People can localize sound sources indoors and outdoors, i.e., almost as well in the presence of reverberation as in its absence 61,62/. They seem to use localization in order to enhance intelligibility as, for instance, when they listen to just one conversation during a cocktail party. (This should, however, not be meant to imply that this kind of "filtering", in listening to one talker at a time, is all a matter of localization).

Let us imagine a man whose head is immersed in a sound field, or a man who is wearing a headset through which acoustic stimuli are being presented. Which aspects of the stimulus do we have to measure in order to be able to predict our subject's ability to localize the direction of the sound source? Again we must distinguish between pure tones and the transient "sounds of nature". In the case of a pure tone we can define a more or less steady-state situation for which there is a definite amplitude and phase relation between the stimulus for the right ear and the stimulus for the left ear. In the case of a complex but steady sound the stimulus situation is characterized by many such relations (this may be the reason why such complex sounds are more readily localized than the laboratory-bred pure tones). Finally there are the changing sounds which for our present purposes we may describe as a series of pulses. In this last instance we can talk about a time relation only: the pulse reaches one ear earlier than the other one.

Let us now inquire how man responds to these various situations. In the case of a pure,steady tone the evidence is strongly suggestive of a double mechanism. For the low frequencies, the phase relation seems to act as the more important clue while for high frequencies the intensity clues seem the more important 63/. In between, around 3000 cps, both these mechanisms seem to feed conflicting information with the effect that pure tones in this frequency region are rather poorly localized. A little reflection on the relation of headsize to wavelength phase information can be of little value at very high frequencies.

If we now examine what happens in the case of pulse-like sounds we find that there are two factors that we can isolate and that contribute to man's ability to point with his eyes closed and say "that's where the sound is coming from". First we find that two pulses reasonably equal in intensity that reach the same ear separated by short time-intervals up to several hundredths of a second are in general judged to be one, namely the first one. The organism seems too busy to digest the "echo-pulse" (or even echo-pulses if there are more than two pulses) to be able to tackle the next one. After a short while the registers clear slowly and another response can be evoked. There is no single time interval that can be given for this unresponsive period. If the second pulse is sufficiently strong it will be recognized at a shorter time interval than when it is barely above the normal threshold.

Now when we feed our two pulses, not to one ear but the first one to the left ear and the second one to the right ear, we find that for really short time intervals the situation is essentially unchanged. Our observer will tell us that there is only a single sound and he will localize it towards the side of his left ear (the one that was presented the first pulse). This "early-arrival" effect permits us to give a reasonable explanation for man's ability to localize sound sources even in rather reverberant rooms. We can, of course, upset this effect or at least neutralize it by modifying intensity relations or by adding a pair of pulses for the purpose of reversing the initial localization. On the whole, things work out pretty well and the average man is able to make reasonably

good localizations for time intervals as short as 12 microseconds* (corresponding to a distance difference in air of something like 0.4 cm!).

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* R. G. Klumpp 64/ has reported some recent measurements of discriminability of interaural time difference. The abstract of his paper reads as follows: "Using earphone presentation and electrical lag lines which allow precise control of time delays, measurements were made of interaural time difference thresholds for pure tones and noise bands. The time difference threshold is here defined as the minimal change in interaural time difference which elicits a perceptible shift in the location of the sound image. Results present the discrimination threshold for interaural time delay as a function of the psychophysical method of measurement, bandwidth and center frequency of the signal. Under optimum conditions, the mean interaural time difference threshold for the five best listeners is about six microseconds. Under similar conditions the mean threshold for 23 listeners is about 12 microseconds."

Masking. Rarely, except in laboratory situations, do we listen to sounds in perfect quiet, i.e., at a noise level that lies below our absolute threshold. Most of the time we are faced with sounds that interfere with our reception of the "signal", i.e., of the acoustic stimuli we are trying to discriminate. This interference with auditory communication by simultaneous stimuli is called masking. The American Standard Acoustical Terminology defines masking in a narrower sense as "the amount by which the threshold of audibility of a sound is raised by the presence of another (masking) sound. The unit customarily used is the decibel." This definition is clearly restrictive in that it excludes a large number of effects to which a masking sound gives rise. It is, however, a realistically restrictive definition in the sense that we have little reliable quantitative evidence on effects other than threshold shifts.

What other effects are there besides the raising of the threshold? Practically all the psycho-acoustic functions we have discussed up to this point are affected. The presence of a masking sound affects the way in which we would scale the loudness of a signal that we are nevertheless able to detect*; it changes the pitch of a tone in a manner that is not easily quantified 58,59/; it modifies the size of the just noticeable differences** and, finally, it has an effect upon localization. It is safe to assume that a masking noise will interfere with what we might call the temporal resolving power of the auditory mechanism, i.e., man's ability to tell that two acousti signals are separated in time. Almost all these effects are in need of further investigation but their existence is too well established to be subject to doubt.

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* The loudness of pure tones in the presence of noise has been investigated by Steinberg and Gardner 65/, while Pollack 66/ has reported how the loudness of speech is affected by a background noise.

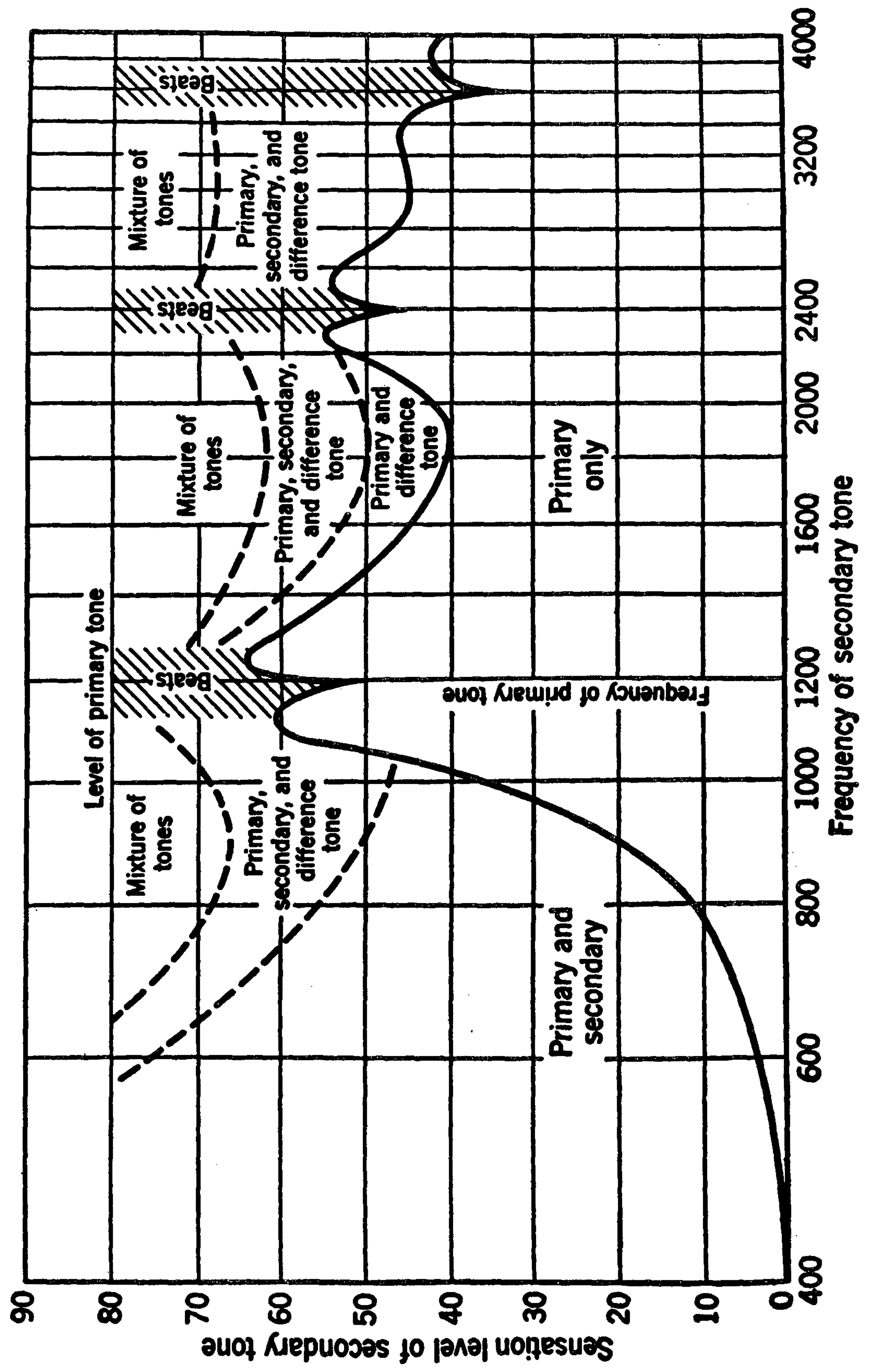
** Harris 67/ has shown, for instance, that frequency discrimination suffers when the signal is not far above its masked threshold. The situation improves radically for signals more than 15 db above their masked threshold.

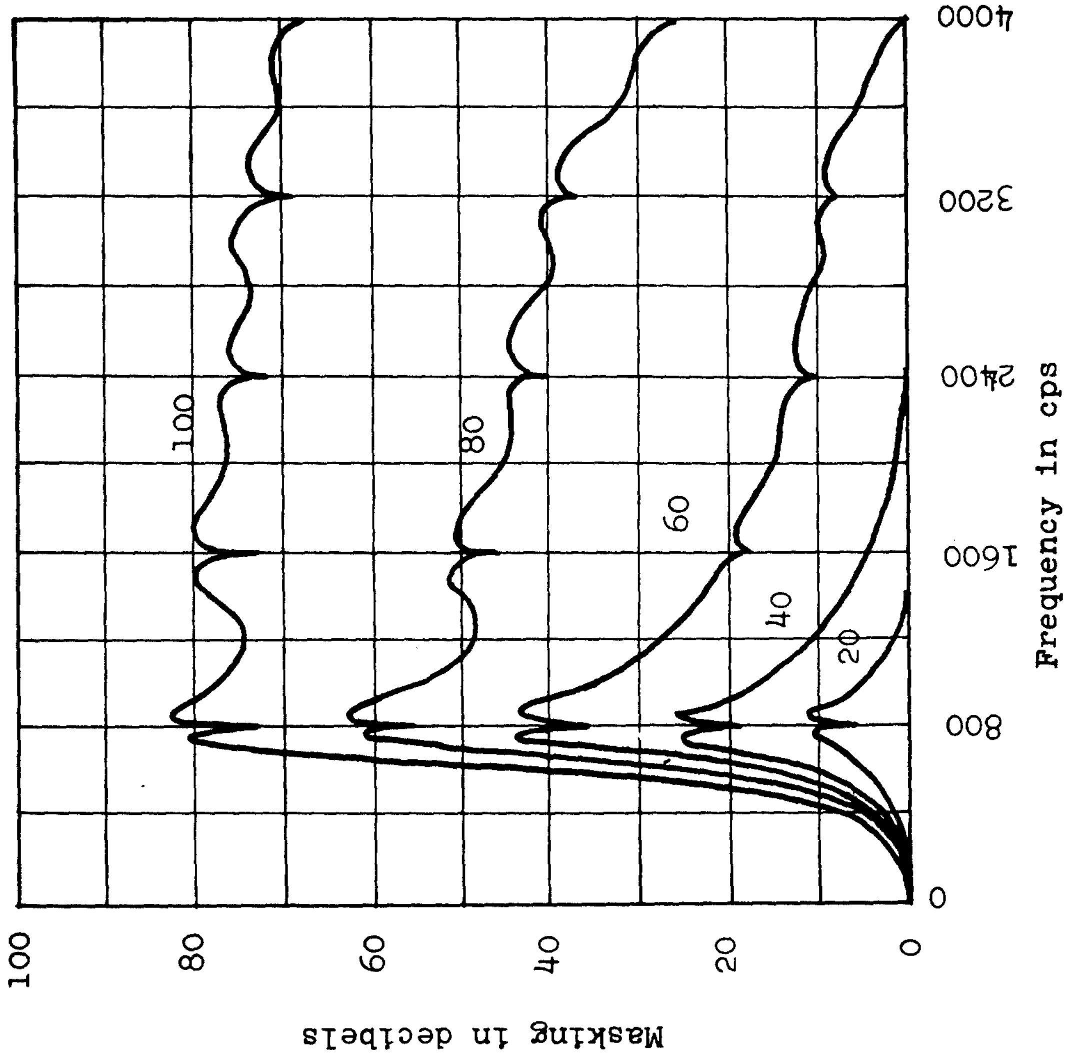
It is obvious that the amount of interference or interaction between two simultaneous stimuli (the masked stimulus and the masking stimulus) will depend very much on what these stimuli are. Presumably two pure tones will behave differently than a combination of a pure tone with wide-band noise. Finally, stimuli having different temporal characteristics will interact in still a different fashion. As we shall see in the following paragraphs, the story of masking is known only in bits and pieces. However, these fragments fit together better than in most other areas of psycho-acoustics, and in principle at least we are able to predict rather well those effects of masking which deal with threshold shifts. As the presence of audible acoustic noise becomes a common occurrence in our lives we shall need to know more about these other effects of masking we described above.

What is a common example of masking? Imagine that you are sitting in your living room during a spring evening. The windows are open and you can make out the traffic noises from a nearby highway. However, these noises hardly interfere with your conversation, which rolls along effortlessly. Suddenly you hear an approaching airplane. You check your watch. He is on time tonight. As the plane approaches, you and your friends have to increase your vocal output if you want to be understood, unless you want to wait until the plane has passed. The fact that you have heard the noise of the plane hundreds of times before does not alter the fact that you still have to raise your voice. (The speech sounds are the masked signal while the airplane noise is the masking signal or the masker.)

Figure 16.13

The masking of a tone (secondary tone) by a primary tone of 80 db SPL and frequency 1200 cps. The ordinate gives the level of the secondary tone in decibels above the threshold level in quiet. The abscissa is the frequency of the secondary tone. Regions in which various combination s of tones are perceived are noted on the graph. (From Wegel and Lane 68/.


Level of primary tone
Mixture of tones
Primary, secondary, and difference tone
Beats
Mixture of tones
Primary, secondary, and difference tone
Primary and difference tone
Beats
Mixture of tones
Primary, secondary, and difference tone
Beats
Primary and secondary
Primary only
Frequency of primary tone
Sensation level of secondary tone
0
10
20
30
40
50
60
70
80
90
Frequency of secondary tone
400
600
800
1000
1200
1600
2000
2400
3200
4000


Masking in decibels
100
80
60
40
20
0
Frequency in cps
0
800
1600
2400
3200
4000
100
80
60
40
20

How shall we describe this masking effect? Let us think of an analogy. Imagine that you are looking for a flower. When it stands by itself, it will be easily discernible against the background of the earth. Now assume that some grass has been growing in the same field; it is clear that the flower will have to have a certain height to be visible. It will also help if the color and the shape of the flower are different from that of the grass. It is further reasonably obvious that only the grass that grows right in the vicinity of the flower will interfere with our seeing the flower, provided the grass is not very tall. It will certainly make a difference on what side of the flower the grass grows if our field is not uniformly illuminated, i.e., if we have light and dark patches. It will help further if we know the flower we are looking for instead of being told "go, look for a flower in the lawn". As you read the material on masking that follows, especially the sections that deal with intelligibility of speech in the presence of noise, you will see for yourself how analogous these two situations really are.

The classical experiments on masking were performed in the early 1920's at the Bell Telephone Laboratories 68/. These experiments involved pure tones as both masking and masked stimuli. They covered a wide range of frequencies and intensities, but there was apparently only one subject involved. Figures 16.13 and 16.14 illustrate some of the phenomena that are encountered when pure tones are used as both the primary and secondary stimuli.

How does a masking experiment proceed? A subject is presented a stimulus situation in which the signal is submerged in the "noise", i.e., the masker swamps the masked stimulus. As the intensity of the masked stimulus is slowly increased, there comes a point where the subject is able to detect a change. This change may be attributable to any one

Figure 16.14

The masking of a tone by a primary tone of frequency 800 cps. The parameter is the sensation level of the primary tone in decibels. The masking in decibels is plotted as a function of the frequency of the secondary tones. (From Wegel and Lane 68/.

of the various masking effects that we have described above, i.e., it may be reported as a change in loudness, a change in pitch, or even a change in localization. This "detection of anything" criterion is probably the safest we can adopt. It points strongly to a parallel between experiments on masking and experiments on JND's.

The main conclusions to be drawn from masking experiments with pure tones can be summarized briefly as follows: (1) there is more masking between tones that lie close to each other in frequency than for tones that are further apart. (2) a low frequency stimulus is more effective in masking a high frequency stimulus than vice versa.

As the intensity of the masker is increased the amount of masking for various frequencies increases, but the amount of increase depends upon the two frequencies involved (See Fig. 16.14). However, since the masking of pure tones is actually complicated by such phenomena as beats and difference tones it seems hardly appropriate here to go into detail concerning these second-order effects. These second-order effects are most clearly present at harmonics of the fundamental frequency of the masker. This is why they have been attributed to so-called aural harmonics. The assumption was made that at sufficiently high stimulus intensities the mechanical structures in the ear would cease to function in a linear fashion, and the deviations from linearity would give rise to these harmonics. This explanation is not unreasonable, and there are undoubtedly stimulus intensities for which the behavior of the ossicles ceases to follow Hooke's law. There are, however, the findings of Békésy 69/ who was apparently unable to detect mechanical vibrations along the cochlear partition corresponding to such harmonics. There is also the fact that these aural harmonics make themselves felt at intensities that are so near threshold values that the assumption of non-linearity is not entirely convincing. It may well be that the nervous system, a non-linear device par excellence, introduces most of the non-linearity, especially at low stimulus intensities. Experimental evidence should soon become available to help us decide the extent to which each of these two explanations is valid.

Recently, experiments by Egan and Hake 70/ have cleared up some of the peculiarities of the Wegel-Lane data. Egan and Hake used as their masking stimuli both pure tones and

narrow bands of noise centered around the corresponding pure tone frequencies. The pure tone maskers yield masking contours that are very much like the Wegel-Lane data. However, the bands of noise give rise to rather smooth masking contours from which beats or difference tones are absent. Masking patterns for the two cases are shown in Fig. 16.15. The two main conclusions we quoted above are still valid, however.

The reader may wonder if we have no information concerning some more realistic masking situations. He will find information on the masking of speech in Sec. 16.4. We shall now attempt to report what happens when the masking noise is "broad-band white noise", i.e., approximately a 7000 cps band, since that represents the pass band of good quality earphones. These masking experiments have been subjected to a thorough theoretical analysis, and important concepts such as that of the critical band have had their origin in these experiments.

When a 7000 cps wide-band noise is used as a masker for pure tones in the audible range (see Fig. 16.16) we find that we have to have an overall SPL of about 20 db before the "masked" thresholds for pure tones are appreciably different from absolute thresholds for normal subjects. As the level of the noise is gradually raised we find that it affects first the thresholds for tones in the most sensitive region, i.e., from 1000 to 4000 cps. Further increase in the intensity of the masking noise yields masking effects all through the frequency range (up to 10,000 cps and presumably above, if accurate measurements could be made in that region). However, for any SPL of the noise, the middle frequencies show the greatest amount of masking, i.e., the largest threshold shift in db. For sufficiently large stimulus intensities of the noise (about 100 db overall SPL) the masked thresholds for pure tones from 100 to 5000 cps are approximately equal in SPL, a situation that resembles our findings for equal loudness contours (Fig. 16.8).

If we replot the data of Fig. 16.16 in order to show masking for pure tones as a function of the SPL of the noise, an interesting fact emerges. We obtain a family of curves which, except for an initial curved portion, are parallel straight lines of slope 1 (Fig. 16.17). This means that for each additional db of noise we will get an additional db of masking.

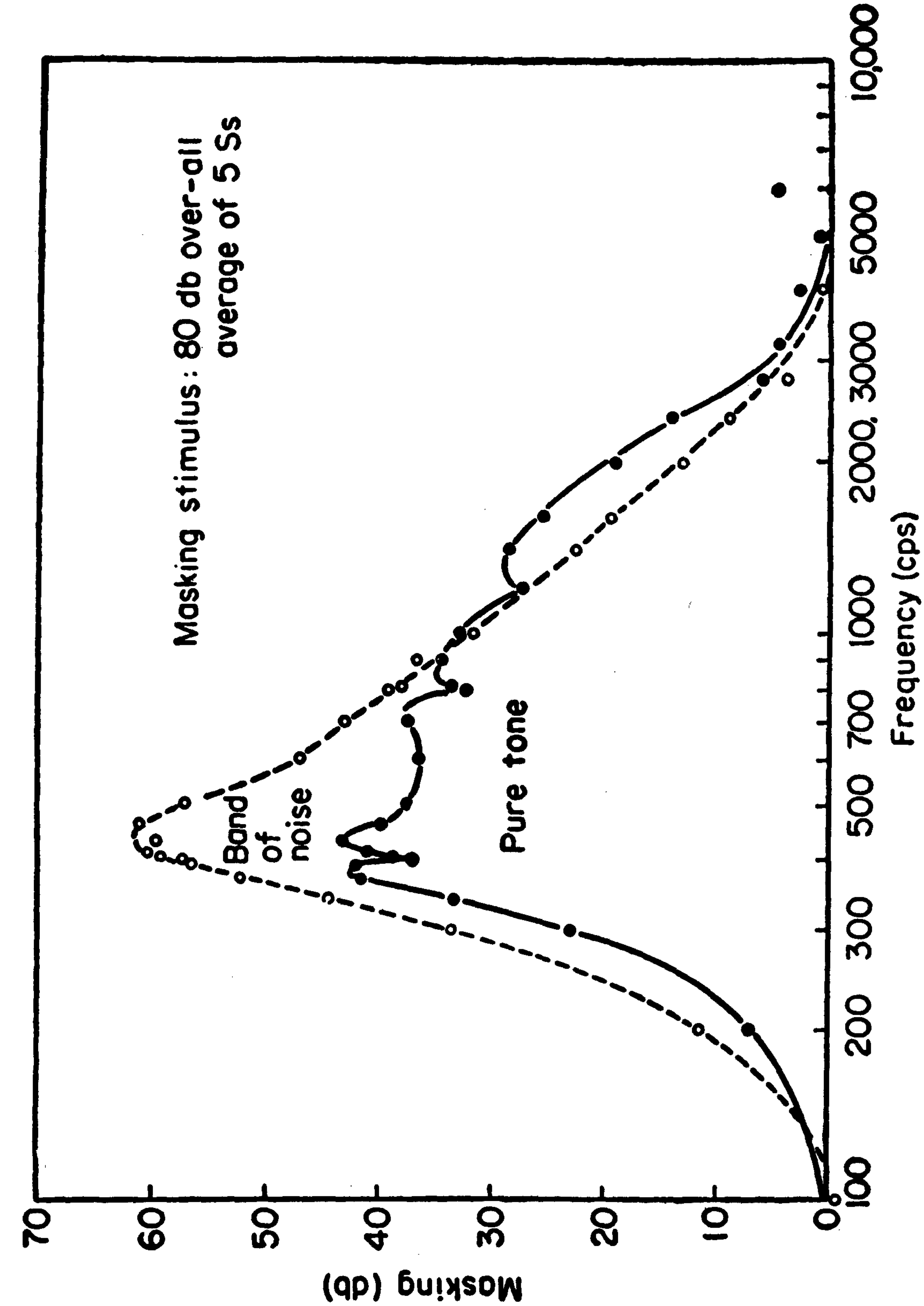
Data such as these in Fig. 16.17 call for a generalization: is there a transformation that will permit us to represent the whole family of curves by a single curve? This was done by Hawkins and Stevens 71/ when they plotted amount of masking M vs the effective level Z of the masking noise (Fig. 16.18). M is simply the threshold shift for a pure tone due to the presence of the noise, while Z is the number of db by which the total energy in a critical band (see below) exceeds the threshold energy for a pure tone whose frequency is at the center of the band. The critical band concept has been put to so much use (and perhaps also some misuse) in the literature on masking that it will be worthwhile to explain it in some detail.

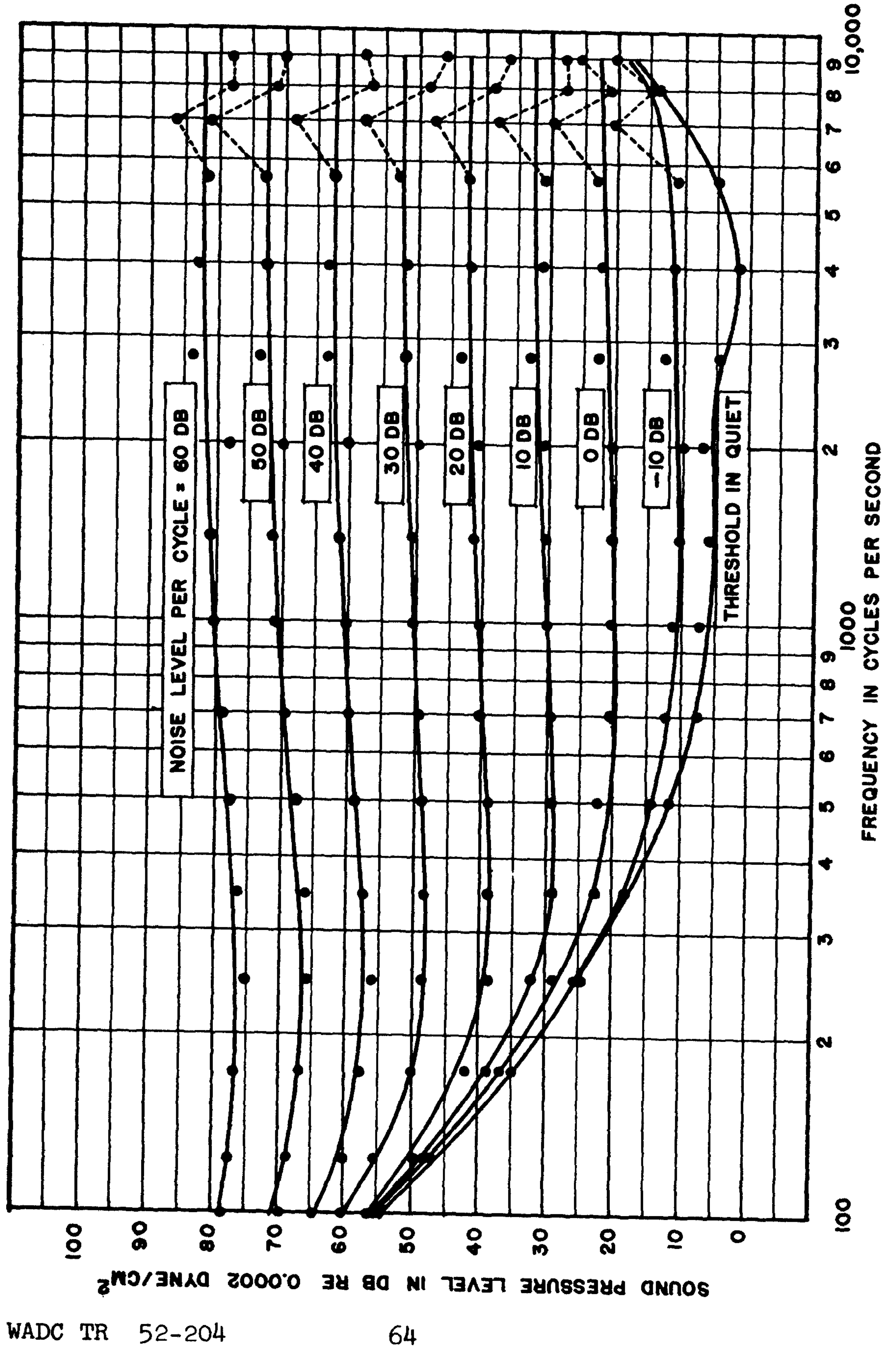
In the early 1930's Fletcher and Munson 40,41/ were interested in the loudness of complex tones and in the relation between loudness and masking. For their experiments they generated a random noise capable of producing approximately the same amount of masking at each frequency. Most of their work was related to a hypothetical model of the basilar membrane. It was thought at the time that much of man's behavior in response to acoustic stimuli could be explained in terms of what was supposed to happen along the basilar membrane*. Whatever the validity of this physiological model in the light of our present knowledge, an important generalization emerged from this physiological-behavioral cauldron: the concept of critical band 39/. This concept is based upon the double assumption: (1) only the frequencies that lie within

* Since that period, Békésy's 69,72,73/ researches have given us a more realistic picture of what goes on inside the cochlea.

Figure 16.15

Masking produced by two stimuli, one a pure tone of 400 cps frequency and the other a narrow band of noise centered at 410 cps. The masking in decibels is plotted as a function of frequency. (From Egan and Hake 70/.


Masking stimulus: 80 db over-all
average of 5 Ss
Band of noise
Pure tone
Masking (db)
Frequency (cps)
0
10
20
30
40
50
60
70
100
200
300
500
700
1000
2000
3000
5000
10,000



NOISE LEVEL PER CYCLE = 60 DB
50 DB
40 DB
30 DB
20 DB
10 DB
0 DB
−10 DB
THRESHOLD IN QUIET
FREQUENCY IN CYCLES PER SECOND
100
1000
10,000
SOUND PRESSURE LEVEL IN DB RE 0.0002 DYNE/CM²

a narrow band centered at the frequency of the tone that is being masked contribute to the masking, and (2) when a tone is just audible against the noise, the energy in the critical band is equal to the energy of the tonal stimulus.

There has been much debate concerning the validity of the concept of critical band. In particular, the curve that represents the width of the critical band as a function of frequency has been under scrutiny. Neither Egan and Hake 70/ nor Shafer and his co-authors 74/ were able to show perfect agreement with a previously published curve. However, one ought to be careful about interpreting the critical band concept too literally. Some have gone as far as to consider the critical bands the contemporary heirs to the resonating structures in the inner ear that throughout the last century explained man's ability to discriminate pitch.

Critical bands permit us to predict to a first approximation the amount of masking for pure tones in the presence of well-behaved noises, i.e., noises having uniform, smooth spectral and temporal characteristics. The critical bands are undoubtedly related to the general mechanism of frequency-discrimination. However, the fact that the Shower-Biddulph DL's for frequency are proportional to the critical bands has been overstressed. Whatever the critical bands are, they do not, as Békésy's data show, represent the sharpness of the resonance curves of the basilar membrane.

Figure 16.16

Contours showing the monaural thresholds for pure tones when masked by white noise at various intensities. The parameter is the approximate level of the masking noise. The sound pressure levels of the pure tones are derived from the calibration data of an earphone into a 6-cc cavity. The dotted portions indicate the nonuniform earphone response at high frequencies. The solid curves are corrected for this nonuniform response. (From Hawkins and Stevens 71/.

A final word concerning critical bands for one ear versus critical bands for two ears: two ears behave definitely *as if* they were more sharply tuned than one. The width of the critical bands for one and two-ear listening are shown in Fig. 16.19. Hirsh's findings on the masked threshold for low-frequency tones as a function of interaural phase would further modify these critical band functions 76/. Let us be satisfied with the fact that over a certain range of man's behavior, the critical band model (a mathematical and not a physical model or even a physiological "reality") represents a useful predictive device.

Not all the data involving pure tones and noise deal with steady pure tones and steady noise. Garner and Miller 78/ have investigated the masked threshold of pure tones as a function of duration, and Miller and Garner 79/ have studied the masking of tones by repeated bursts of noise.

Hirsh, Rosenblith and Ward 80/ have investigated the masking of brief clicks by pure tones and bands of noise. In such experiments new elements enter the situation involving the temporal characteristics of both masking and masked stimuli. These experimental data exhibited greater variability among subjects with normal audiograms than is customary in masking experiments, which are usually characterized by somewhat less variability than absolute or differential threshold measurements.

Stevens 36/ has described some masking experiments in which sounds of a more complex nature were used as either maskers or masked stimuli. He generated a complex, buzz-like tone by excitation of a single electrical resonant circuit with a periodic (125 cps) sequence of pulses. Such a stimulus is similar in nature to a vowel sound, which is generated by periodic excitation of the resonant vocal cavities. Two groups

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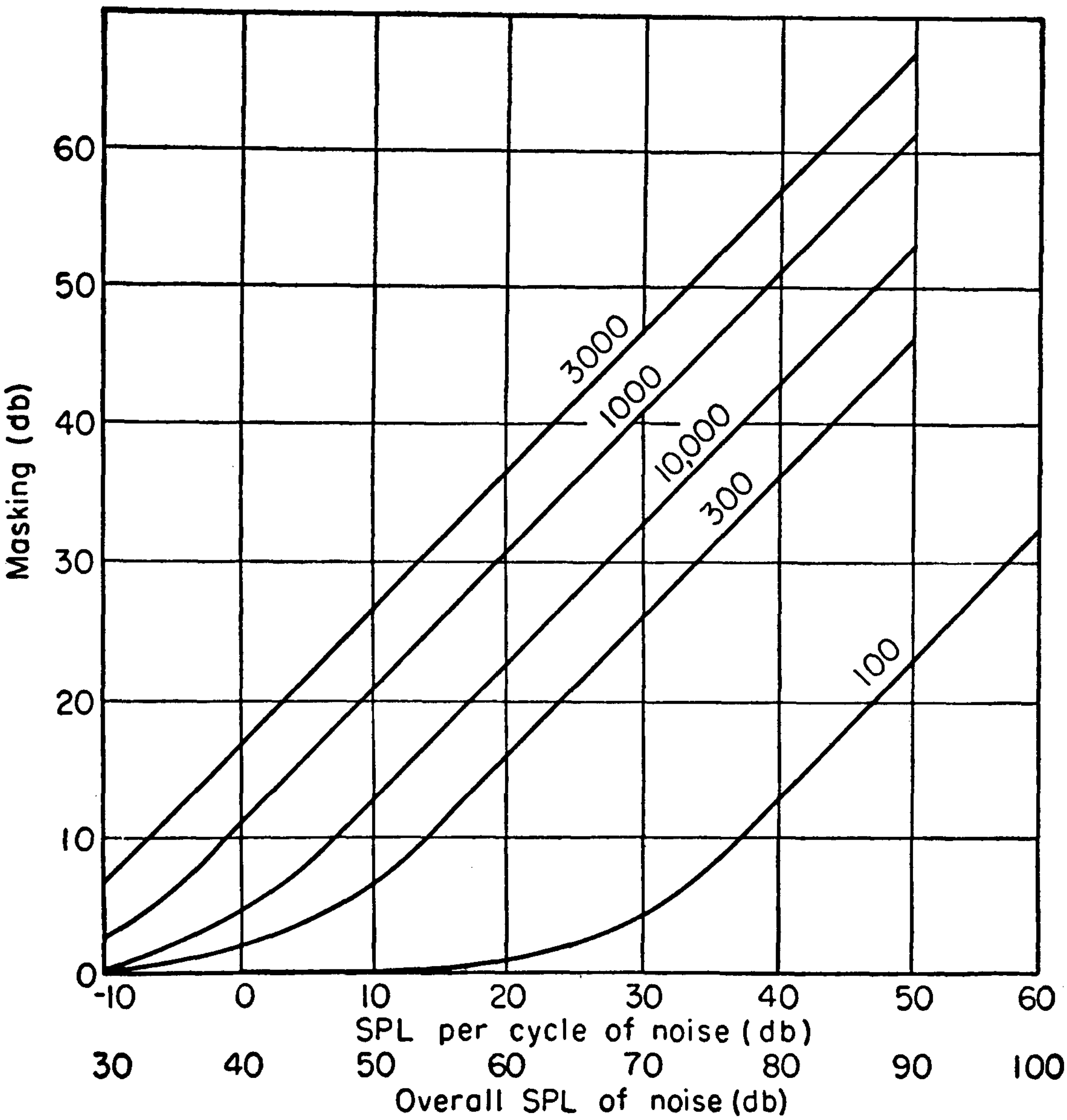
Figure 16.17

Relation between the masking of pure tones of various frequencies and the level of the masking noise. Two abscissas are shown. One indicates the overall SPL of the masking noise in a 7000 cps band, and the other indicates the SPL per cycle of the masking noise. (From Hirsh 19/, after Hawkins and Stevens 71/).

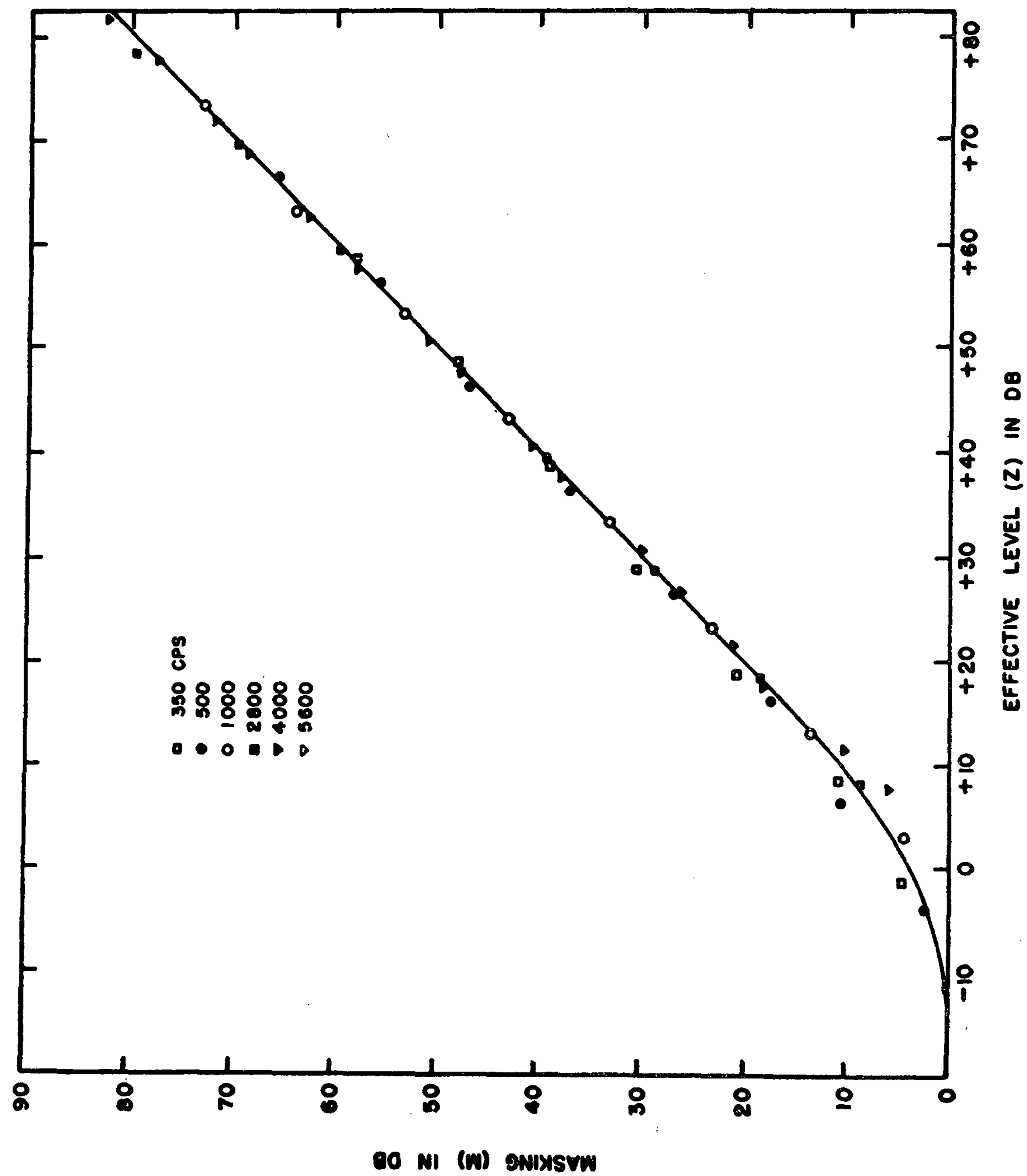

Masking (db)
0
10
20
30
40
50
60
3000
1000
10,000
300
100
-10
0
10
20
30
40
50
60
SPL per cycle of noise (db)
30
40
50
60
70
80
90
100
Overall SPL of noise (db)

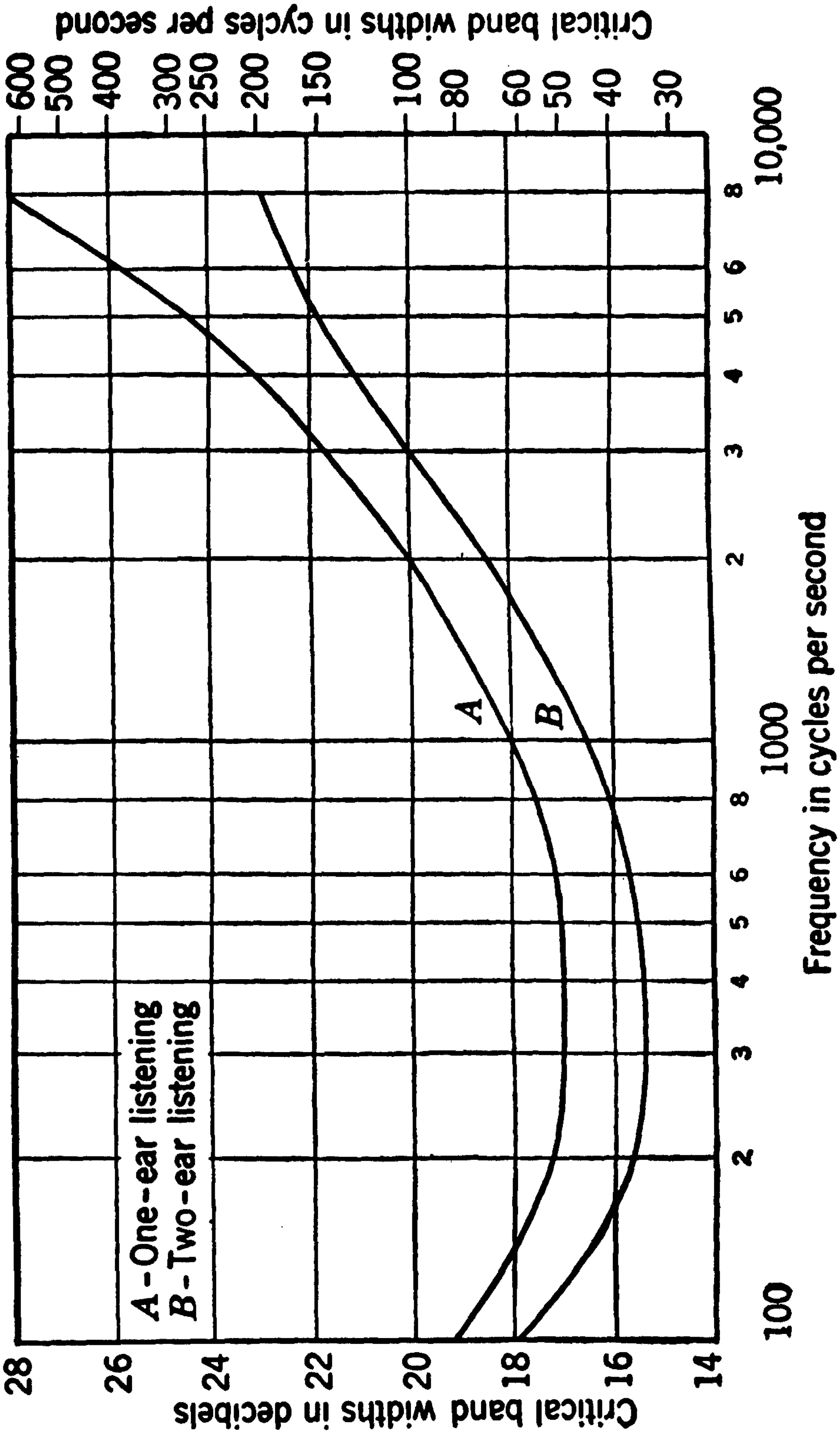
of masking experiments were performed: (1) the buzz sound was used to mask pure tones, and (2) pure tones and bands of noise were used to mask the buzz sound.

At the beginning of this section, we said that we would deal only with effects attributable to the simultaneous presence of a signal and a noise. Lately investigators have lumped after-effects of short duration under the heading of masking (see de Mare's "After-Effect Masking" 81/ and Munson and Gardner's "Residual Masking" 82/. Without desiring to enter here into a semantic argument, let us state that we will deal with those observations in the next chapter. This postponement does not mean that after-effect phenomena are any less basic; the division of the material is merely a matter of convenience.

Figure 16.18

Relation between the masking (M) and the effective level (Z) of the masking noise. Z is the number of decibels by which the total energy in a critical band exceeds the threshold energy for a pure tone whose frequency is at the center of the band. (From Hawkins and Stevens 71/).


350 CPS
500
1000
2800
4000
5600
EFFECTIVE LEVEL (Z) IN DB
-10
0
+10
+20
+30
+40
+50
+60
+70
+80
MASKING (M) IN DB
0
10
20
30
40
50
60
70
80
90


Critical band widths in cycles per second
600
500
400
300
250
200
150
100
80
60
50
40
30
A
B
A - One-ear listening
B - Two-ear listening
Critical band widths in decibels
28
26
24
22
20
18
16
14
100
2
3
4
5
6
8
1000
2
3
4
5
6
8
10,000
Frequency in cycles per second

16.3 Audiometry

In its broader sense, audiometry means "measurement of hearing." Usually, however, the term is used to describe a restricted kind of auditory measurement, namely the measurement of the absolute threshold for pure tones and for speech. The instrument used to perform this kind of measurement is called an audiometer.

In Section 16.2 we discussed in some detail how thresholds for pure tones can be measured in the laboratory. We have shown (Fig. 16.1) curves of minimum audible field and minimum audible pressure measured by several investigators in careful laboratory experiments. These are the threshold curves for young subjects with acute hearing. These threshold curves are, in a sense, examples of experimental audiometry in contrast to clinical audiometry. Hirsh 19/ distinguishes between these two kinds of measurement: experimental audiometry is concerned with the measurement of thresholds in terms of the physical dimensions of the stimulus, whereas clinical audiometry has to do with the measurement of hearing loss, i.e., the difference between a particular threshold and a comparable threshold norm.

The need often arises for measurements of the hearing of an individual in a non-laboratory situation. To evaluate the hearing of this individual, we should like to compare such measurements with those for individuals with normal hearing. The measurement is most often made in a room that is not absolutely quiet, such as a doctor's office, where the ambient noise is likely to interfere somewhat with the measurements. The person operating the audiometer is usually not skilled in the techniques of psychophysics, and the subjects are certainly not trained. Such clinical measurements clearly fall into a class entirely different from the laboratory measurements discussed previously. We must devise special techniques that

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Figure 16.19

Critical bands for one- and two-ear listening. The left-hand ordinate gives the bandwidth in decibels, as $10 \log_{10} \Delta f$. The right-hand ordinate is Δf in cps. (From Beranek 75/, after French and Steinberg 77/).

are suited to the clinical situation in order to be sure that meaningful results can be obtained.

To the otologist and audiologist, audiometry is a useful aid in the detection, diagnosis and correction of diseases of the ear. The usual type of measurement consists in determining the absolute threshold for pure tones. The data are plotted as hearing loss relative to the threshold norm. Often, however, it is necessary to measure the amount by which the hearing of an individual differs from normal hearing in order to evaluate the extent to which his loss of effectiveness as a member of society is influenced. There are many ways in which partial or complete loss of hearing may adversely influence our effectiveness in society. Our ability to understand speech may be impaired; our ability to perceive distance and direction may be influenced; our enjoyment of music and other sounds may be affected; our well-being or the well-being of others may be influenced by our inability to hear sounds of warning or distress.

Classically the accepted audiometric technique has been the measurement of the absolute threshold for pure tones relative to that of a normal population. Before the advent of the electronic audiometer, tuning forks and tests involving spoken and whispered speech were often used to measure hearing acuity. It is reasonably obvious that our ability to perceive speech is related to the amount of hearing loss for pure tones. However, the exact form of this relation is not completely understood at present. It would lead us too far astray to go into the reasons for this difficulty at this point. Suffice it to say that a given amount of hearing loss may affect speech perception very differently depending upon the nature of the loss 19/. (See below for a discussion of various kinds of loss).

Fletcher (1929 83/ and 1953 84/) and Carhart 85/ have derived relations between the pure tone threshold and the reception of speech. In 1942 The American Medical Association sponsored a method for calculating the "percentage hearing loss for speech" from the audiogram. This method has been used widely in recent years, but its nature has been misunderstood by some who have used it. At present, an attempt is being made to define medico-legal standards in which hearing loss for pure tones at certain frequencies is related to a measure of socially useful hearing for speech.

Recently, as psycho-acousticians have developed quantitative techniques for testing the intelligibility of speech, considerable emphasis has been placed on speech audiometry. Many investigators believe that auditory measurements that involve speech stimuli directly are more closely correlatable with social adequacy 86/ and other related factors than are pure tone measurements.

The use of speech as the test material has certain disadvantages, since the intelligence, training, and even regional background of the subject plays a significant role in determining his response to speech items. Perhaps an audiometric technique which measures the perception and discrimination of speech-like sounds (such as damped waves, clicks, bands of noise) would constitute a meaningful and at the same time practicable method for measuring hearing loss.

The discussion which follows is limited chiefly to pure-tone air-conduction audiometry and speech audiometry. The results of some large-scale audiometric surveys follow the section on pure-tone audiometry, since those surveys were helpful in establishing the normal audiometer threshold and in estimating the expected deviations from this threshold. In particular, the shift in the audiometer threshold with age is discussed in some detail.

Audiometric procedures that are useful only in the diagnosis of hearing defects and in the screening of groups of subjects are not emphasized since, for the purposes of this handbook, they are of little interest.

Pure-Tone Audiometry. The hearing loss for pure tones* is generally measured at each of several frequencies, usually

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* The discussion in this section is restricted to the determination of thresholds for air conduction for which the stimulus is applied by means of an earphone. In the diagnosis of certain hearing defects, bone-conduction thresholds are occasionally used. Skilled otolgists can use these tests to good advantage for purposes of diagnosis. These test results are, however, still more difficult to interpret in terms of the understanding of a speech than the results of pure tone audiometry using air conduction.

covering the range from 125 to 8000 cps. Hearing loss is expressed as the number of decibels by which the intensity of a pure tone must be raised above a "normal" threshold intensity in order that it will elicit a response from an observer. Earphones are invariably used to present the stimulus in turn to each ear of the observer.

In Section 16.2 a discussion is presented of the absolute threshold of hearing as determined from laboratory measurements. Two types of threshold are defined: a minimum audible field (MAF), in which the sound pressure is measured at the location of the center of the head in a free-field before the head is inserted in the field, and a minimum audible pressure (MAP) in which the sound pressure is measured at the eardrum by means of a probe tube. The MAF and MAP threshold curves are shown in Fig. 16.1. Neither one of these curves is used as the "normal" threshold for an audiometer.

Usually audiometric measurements are not made under ideal laboratory conditions, where great care can be taken to minimize the ambient noise level and to use well-trained subjects. In many spaces where audiometers are used the ambient noise level is sufficiently high at low frequencies to mask the low frequency tones generated by the audiometer near the threshold level. The masking at medium and high frequencies (above 500 cps) is usually small, however, since the spectrum of the ambient noise drops off rapidly at high frequencies. Another difficulty in clinical audiometry is that probe-tube calibrations are difficult to perform, and are subject to some variability from observer to observer because of differences in fit of the earphone and differences in ear canal dimensions. Consequently, the "normal" audiometer threshold is defined in terms of the sound pressure developed by the earphone in a standard coupler when the audiometer is set at zero decibels hearing loss.

In its standards on "Minimum Requirements for Acceptable Pure-Tone Audiometers for Diagnostic Purposes", the American Medical Association has specified a National Bureau of Standards Coupler 9-A or its acoustic equivalent 87/, and has specified the threshold sound pressures developed in that coupler for several types of earphones. For a Western Electric Type 705-A earphone, the threshold pressures are given in Table 16.1. For comparison, the MAP and MAF data of Sivian and White 1/ are also shown in the Table. (It is interesting to note that the

TABLE 16.1

AMA STANDARD THRESHOLD SOUND PRESSURES FOR AUDIOMETERS USING W. E. TYPE 705-A RECEIVER. MAF AND MAP THRESHOLDS OF SIVIAN AND WHITE ARE SHOWN FOR COMPARISON

Frequency	Threshold Sound Pressure in db re 1 dyne/cm^2		
cps	AMA Standard	MAF	MAP
125	-19.5	-47	-33
250	-34.4	-58	-49
500	-49.2	-67	-60
1000	-57.3	-70	-67
2000	-57.0	-76	-69
4000	-58.9	-80	-66
8000	-53.1	-64	-55

difference between the MAF and the AMA standard is as much as 27 db at low frequencies). The normal threshold specified in this fashion by the American Medical Association was established from measurements of thresholds for a large number of ears of persons in the age group of 18 to 30 years inclusive*.

The hearing loss, therefore, is the number of decibels by which the intensity of a pure tone must be raised above the normal threshold intensity defined in Table 16.1. In a sense, the pure-tone hearing loss of an individual is equal to the sensation level of the pure tone for an AMA standard observer. The data for a given subject are usually presented in the form of an audiogram, which is a plot of the hearing loss, in

* A further discussion of the problems involved in establishing a normal threshold for audiometers is given later under the effects of age.

decibels, as a function of frequency. A typical audiogram is shown in Fig. 16.20.

Users of audiometers employ many different techniques for the measurement of hearing loss, and at present there are no accepted standard procedures. For example, the definition of hearing loss given at the beginning of this section fails to specify how the pure-tone stimulus is presented to the observer during the test, or how the response of the observer is measured and evaluated. Questions of instrumentation, environment and psychophysical procedure are discussed below.

The stimulus is generated by a pure-tone audiometer, which comprises three units: (1) an electronic oscillator for generating alternating electric currents of the desired frequencies, (2) an amplifier with an attenuator, and (3) an earphone for applying the sound to the listener's ear. The sound pressure level of the sound is adjusted by means of the attenuator dial, which is calibrated in units of hearing loss (decibels). The frequency of the sound is selected by means of another control which is marked in cycles per second. An audiometer should be equipped with a switch for turning the tone on and off without introducing audible clicks.

The Council of Physical Medicine and Rehabilitation of the American Medical Association and the American Standards Association have written specifications on minimum requirements for acceptable pure-tone audiometers for diagnostic purposes. The "normal" threshold sound pressures contained in these specifications have been tabulated above. In addition the requirements specify test frequencies, intensity intervals and ranges, as well as acceptable harmonic distortion and noise present in the signal. The Standards also provide a list of accepted commercial audiometers.

Testing techniques for the measurement of the hearing loss for pure tones have been suggested by several investigators,

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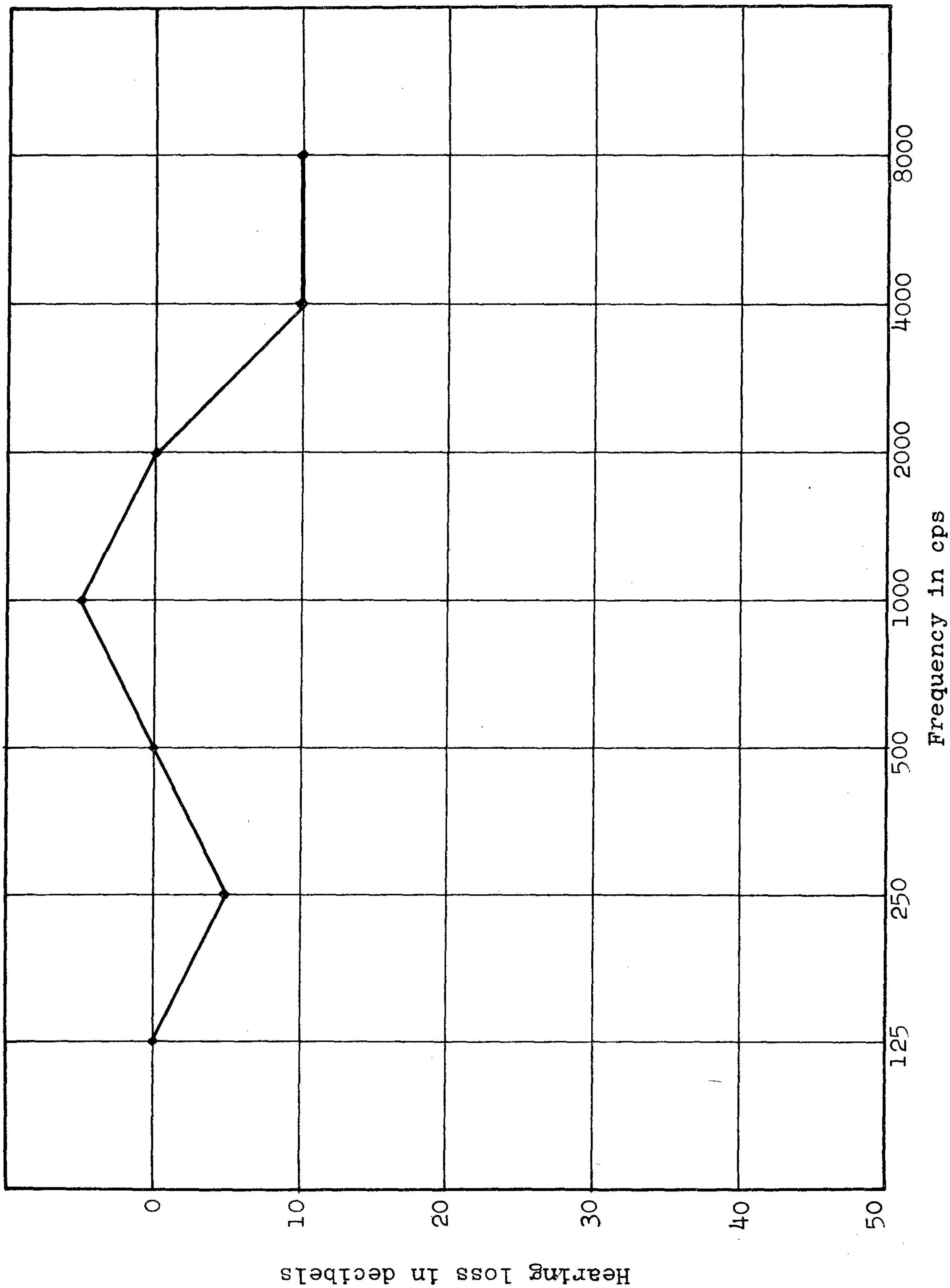
Figure 16.20

A typical audiogram. The hearing loss in decibels is plotted at each of several frequencies.



125
250
500
1000
2000
4000
8000
Frequency in cps
0
10
20
30
40
50
Hearing loss in decibels

and a review of several procedures has been presented by Hirsh 19/. Reger 88/ has given a discussion of some of the factors which influence the accuracy of the measurement, and has proposed a standardized technique which is fairly close to that already followed by many users of audiometers.

Most of the factors which influence the accuracy of auditory thresholds may be classified under the following three subdivisions: (1) variables associated with the environment, (2) variables associated with the subject, and (3) variables introduced by the user of the audiometer.

Of the environmental factors, the level of the ambient noise in the testing room is usually the most difficult to control. It is essential to maintain low noise level in the room. The noise usually present in a building interferes primarily with the detection of the low-frequency tones, and does not appreciably affect detection of the high frequencies. The noise level would be considered sufficiently low if an individual with known normal hearing were able to perceive each frequency at the zero level on the audiometer.

Suppose we wish to assess the hearing loss of an individual or group of individuals on the basis of measurements with a given audiometer in a given environment. In order to interpret our data properly, we should like to know how the normal population would test with the same audiometer and the same environment. In practice, audiometric data should be obtained for a control group that is believed to be representative of the normal population. (See Williams and Cox 89/).

Other variables associated with the environment are those which influence the body comfort and alertness of the observer, and influence his ability to relax during the test. These include the temperature, humidity, and barometric pressure or altitude of the test room, and the time of day. The earphone should be well-fitting, but should not press so hard against the observer's ear that it is uncomfortable.

Psychological factors associated with the subject include his intelligence, reaction time and previous test experience, his physiological condition and his attitude toward the test. Additional test difficulties are presented by subjects who experience head noises such as tinnitus. Malingering and psychogenic disorders fall into still another category.

The training, experience, insight and personality of the person administering the test are important factors. Of primary importance are the techniques he uses to present the stimulus and his evaluation of the subject's response. For example, the stimulus may be presented as a continuous tone or as a tone interrupted at various repetition rates, and the intensity of the tone may be either increased or decreased gradually during determination of the threshold. The value of the threshold may be markedly influenced by these and other factors.

First let us examine the general psychophysical procedures that are available for the measurement of the auditory threshold. The method of adjustment may be used in which the observer himself adjusts the intensity of the stimulus by means of an attenuator until the tone is "just audible". Usually the median of several determinations of the threshold with both ascending and descending intensity is taken as representing threshold intensity. A second procedure, known as the method of limits, is similar to the method of adjustment except that (1) the experimenter, not the observer, controls the intensity, and (2) the approaches from above and below are accomplished at a fixed rate within fixed limits. The observer is instructed to raise his finger whenever he hears the tone and to drop it as soon as the tone disappears. The median intensity recorded for several such determinations is taken as representing threshold intensity. Third, the method of constant stimuli may be utilized. A number of tones of different intensities are presented to the observer, who is asked to respond "yes" or "no" to each tone. The responses are plotted on a graph and the threshold intensity is usually taken as the intensity at which the subject gives "yes" responses 50% of the time.

The traditional clinical audiometric technique is a modification of the method of limits, and makes use of the conventional audiometer described above. The observer is seated comfortably in such a position that he can see neither the control panel of the audiometer nor the hands of the operator. He is instructed to raise his finger or press a signal button whenever he hears a tone, and to withdraw his finger or release the button whenever the tone disappears.

The operator starts with a tone that is well above threshold and gradually reduces its intensity until the observer indicates that he no longer hears it. Some operators leave the

tone on continuously while changing the intensity. Others interrupt the tone either regularly or randomly, and adjust the attenuator (usually in steps of 5 decibels) only during the silent intervals. Random interruption of the tone is believed by many to be preferable, since in this case the subject does not respond to a temporal pattern and is forced to make judgments to each stimulus more or less independently. Once the tone has become inaudible, the intensity is increased until the observer again signals that he hears the tone. The mean of the hearing loss readings on the audiometer for the two directions of approach is recorded as the correct hearing loss. The procedure is usually repeated several times, and the median of several determinations is plotted on the audiogram at the proper frequency, using a symbol appropriate for the ear being tested. The procedure is repeated for each ear separately at frequencies of 125, 250, 500, 1000, 2000, 4000 and 8000 cps, as specified in the standards for audiometers. Formerly, frequencies of 128 cps and multiples thereof were used as test stimuli. However, it is doubtful if a frequency of 4096 cps could really be specified to more than two significant figures. Recent medico-legal thinking would like frequencies of 750, 1500 and 3000 cps to be used in the hope that correlation between pure-tone thresholds and speech audiometry could be improved thereby.

The above discussion, together with certain relevant comments in Section 16.2, indicates that a standardized procedure for audiometric testing is essential if data on hearing loss measured by different groups are to be compared. For example, if the pure-tone hearing loss of a given individual is to be compared with the average hearing loss for his age group (as obtained from one of the national surveys), it would be most desirable to use the same testing procedure in both cases. A standard should specify the order in which different frequencies are to be presented to the two ears, the intensity of the tone at the initial presentation, and the timing of the stimulus presentations. It should also specify the response of the listener that defines the threshold.

Speech Audiometry. In the past, hearing loss for speech was measured without the benefit of a monitoring meter or other electronic instruments. A clinician would stand, say 20' away from a patient, and speak numbers or words for the patient to repeat. The patient's hearing would be considered satisfactory if he could repeat all the test items. If he could not, the clinician moved closer than 20', to a point

where the patient could repeat the words and numbers satisfactorily. The distance then provided a measure of the hearing acuity of the patient for speech. The discussion that follows will indicate that wide variability would be expected for tests conducted in such a manner because of differences in noise level, in acoustic characteristics of the test room, in test material, etc. Reliable results can be obtained only by the proper use of a speech audiometer.

In order to perform acoustic measurements of hearing with speech as the test material, we must (1) present specified speech stimuli to the ear of a listener at known intensities and (2) evaluate the response of the listener to the speech material. Let us first consider the problems involved in the generation of speech signals of known intensities.

The next section (16.4) describes some of the physical properties of speech, and indicates that speech sounds have a wide range of intensities. There are pronounced fluctuations in the instantaneous speech intensity as different speech sounds are uttered in words or sentences. Even the speech intensity averaged over a syllable or word varies from word to word for a given talker, and also varies markedly from talker to talker. The intensity also varies with distance from the talker. Thus, in order to generate standard speech material of known and controlled intensity, we must provide some means for monitoring the intensity. This is usually accomplished by means of a meter that rectifies and averages the speech wave over a fraction of a second. The intensity of a sequence of test items is then adjusted to provide as closely as possible the same peak deflection of the monitoring meter.

The essential elements of a speech audiometer.are (1) a source of speech, either (a) the voice of the operator or (b) a recording, usually a phonographic disc or a magnetic tape, (2) a transducer appropriate to the source; i.e., a microphone, a turntable and a phonographic pickup, or a magnetic tape playback, (3) an amplifier, (4) a meter or other device for monitoring the output of the amplifier to a known or predetermined level, (5) an attenuator, (6) a calibrated earphone or earphones. Minimal requirements for speech audiometers have been proposed by the American Medical Association 94/. These requirements specify the acceptable electrical characteristics of the components of the speech audiometer, including the frequency response, distortion and noise, dynamic range and accuracy of calibration.

Suppose we have a speech audiometer that satisfies the minimum requirements, and we are able, therefore, to present to the ear of a listener speech material of known intensity. Our objective is to measure the ability of the listener to hear and understand speech. Two important aspects of the measurement must be specified before we can perform the test. First the type of test material must be specified, and secondly we have to agree upon the method of measuring the response of the listener. These questions are discussed in some detail in Section 16.4 (in connection with articulation testing methods and the effects of distortion upon intelligibility), and consequently only a few comments are presented here.

The usual procedure is to present a sequence of test items (which may be sentences, digits, spondees, monosyllabic words or nonsense syllables) to the listener, and to ask him to repeat or to write down the items he thinks he hears. The percentage of test items recorded correctly is termed the articulation score. It is fairly obvious that as we increase the intensity of speech from a low value toward a high level, the articulation score will increase. Figure 16.23 19/ shows the relation between articulation score and relative intensity for three different types of words: spondees, unselected dissyllables, and PB (phonetically balanced) monosyllables 9/. The abscissas for the three curves are scaled in decibels relative to the intensity at an articulation score of zero percent. We note from the figure that both the absolute value of the articulation score and the sensitivity of the score to changes in intensity depend upon the test material. The spondees give the steepest function, and therefore are apparently the most homogeneous with respect to intelligibility, i.e., all the spondees are almost equally intelligible.

In clinical speech audiometry, two types of tests are conventionally used. These tests measure (1) the threshold of intelligibility or the hearing loss for speech, and (2) the articulation score, or discrimination loss. The "hearing loss for speech" is the ratio, expressed in decibels, of the threshold for speech to the normal threshold for speech for the particular ear under test. The threshold of intelligibility is the intensity which yields an articulation score of 50%. As noted above, the normal threshold depends upon the test material. Spondees are frequently used in this type of test because the articulation curve (Fig. 16.23) is, as we have seen, relatively

steep. Spondees provide, therefore, a rather sensitive measure of hearing loss for speech*.

Although the hearing loss for speech usually provides a measure of ability to hear speech at relatively low intensities, it is not necessarily too strongly correlated with the intelligibility obtained at relatively high intensities. Two subjects with the same hearing loss for speech i.e., the same speech reception threshold may yield articulation scores which are quite different when the speech is presented at a relatively high intensity. The articulation score for a subject who exhibits a moderate conductive hearing loss will usually rise to about 100% if the speech intensity is sufficiently high. A subject who exhibits a good deal of hearing loss at high frequencies (of the type that characterizes nerve deafness) may not hear the high frequency components of speech at any intensity, and consequently his score may approach an asymptotic value of less than 100% at high speech intensities.

It is desirable, therefore, to measure the "discrimination loss" in addition to the "hearing loss for speech" if a more detailed evaluation of an individual's hearing of speech is required. By definition, the <u>discrimination loss</u> is the difference, in percentage points, between the normal score for an articulation test and the score for the individual under test. This form of test is usually administered at an acoustic level

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* The Central Institute for the Deaf in St. Louis, Missouri has prepared a series of word lists consisting of spondee words and of PB words. The lists have been recorded both at constant level and at decreasing level (to expedite threshold measurement). The tests consisting of spondee words are called Auditory Tests No. W-1 and W-2; the PB lists comprise Auditory Test No. W-22. These tests are available on 12" phonograph records at either 33 1/3 or 78 rpm from Technisonic Laboratories, 1201 South Brentwood Boulevard, St. Louis, Missouri. The normal thresholds for these tests are: spondees, about 18 to 20 db; PB's about 25 db re 0.0002 dyne/cm^2.

well above the threshold for speech, and the test material usually consists of monosyllabic words. The normal value of discrimination (or articulation score) for each test must be determined empirically.

The brief discussion presented above indicates that we can devise relatively simple methods for the measurement of hearing for speech. One or two numbers can be used to describe effectively the abilities of an individual to hear and reproduce speech. These figures permit us also to compare the individual tested with the "normal" population. However, these numbers mean little unless a complete description is given of the test material, the method of administering the test, and the procedure for evaluating the response for both the normal population and the individual under test. It is hoped that standards will be set up that will remove many of these uncertainties. Standard speech material should be recorded for use with standard speech audiometers. The normal thresholds and their distributions should be determined, and the recommended method for administering the test should be described in detail. Only if such standards are established can measures such as the hearing loss for speech and the discrimination loss be extensively used to evaluate loss of auditory function.

The Effects of Age Upon the Absolute Threshold for Pure Tones. Whenever audiometrists are interested in assessing an individual's ability to hear, the question of the effect of aging upon hearing arises. Since the relation of age and age-related hearing loss occupies a rather considerable place in literature, it seems appropriate to discuss this matter in some detail. As medico-legal standards concerning the effects of noise upon hearing are being considered the problem of age is bound to gain in importance.

In 1929 the first important survey of the effects of age upon auditory sensitivity was undertaken. Up to that time there were isolated observations that indicated that the upper frequency limit of hearing decreases in old age. In 1929 Bunch 90/ examined the hearing of more than 350 patients at Johns Hopkins Hospital who had not given any obvious indication of deafness. There were 68 subjects between 20 and 29 years of age, 70 between 30 and 39, 78 between 40 and 49, 85 between 50 and 59 and finally 52 who were above 60 years of age. Bunch

tested at frequencies between 32 and 16,384* by means of a Western Electric Type 1A audiometer.

Bunch's findings have been redrawn by Morgan 91/ into the set of curves of Fig. 16.21. These curves illustrate a fact that has been confirmed in all studies made since 1929, that there is a steady decline in the hearing acuity for the higher frequencies as a person advances in age.

Since Bunch's time there have been several studies of the effect of age upon auditory acuity. Most of the data have been collected at World's or County Fairs. The study of the Bell Telephone Laboratory 5/ included many thousands of subjects in each age group**. Five frequencies were used: 440, 880, 1760, 3520, and 7040 cps. The maximum hearing loss that could be recorded for the two highest frequencies was respectively 46 db (3520 cps) and 33 db (7040 cps). The average data for the various age groups are shown on Fig. 16.22. While the general trend of these data is not too different from those reported by Bunch or by the U. S. Public Health Service 7/, they exhibit an additional trend that has since been confirmed: namely, that while men in the older age group exhibit a greater high frequency loss than women, at low frequencies the hearing loss for men is less than that for women of the same age group. While these data are valuable they still leave a certain number of questions unanswered. There is, for example, no good way of estimating how representative of the population of this country these subjects were. The paper by Steinberg et al 5/ discusses some of the aspects with respect to which the sample was probably biased. The Fair groups (both in New York and San Francisco) seemed to be above average in intelligence, amount of education and economic status. The sample also included a larger than average proportion of urban residents. There is some evidence that all these factors

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* We should be rather cautious about accepting some of these specifications, such as the frequency specified for five significant figures or the calibration of the earphone at the higher frequencies.

** The data on the subjects' age were based upon estimates by attendants.

(with the possible exception of the last one) tend to present too favorable a picture of the hearing of the general population.

There are, however, other important questions that can be raised. Did the people who had their hearing examined go to the test booths because a larger percentage than normal among them was aware of hearing impairment? Only about 80% of the visitors who had their hearing tested permitted the attendants to make a photographic record of the results. Were these 80% an unbiased sample or were people whose test showed them to have impaired hearing less willing to have their losses recorded?

Many of these questions and difficulties were either answered or overcome at the San Diego County Fair 92/. Here hearing tests were administered to 3666 subjects at the same frequencies that had been used in the Bell Laboratory's study. Testing took place in individual booths in an ambient noise level between 35 and 45 db (as read with network A of the standard sound level meter). Each booth contained a headset with donut cushions. The softest test item was discriminable against the background noise of the record. Careful instructions and practice tests were given the subjects before they started the part of the test that was actually scored. The whole procedure took about eight minutes for each subject. Every participant's test paper was retained together with his answers to questions concerning age group, sex, past exposure to noise, musical training and a statement concerning the subject's awareness of hearing difficulties.

Table 16.2 shows the mean and median sound pressure levels at threshold for the 20-29 year age groups, measured at San Diego. Also shown are the monaural data of Sivian and White 1/, and the data from the World's Fairs. The range of sound pressure levels measurable on the instrument at San Diego is also indicated. Since the instrument has a limited range, there are some subjects who may either still hear the softest tone or

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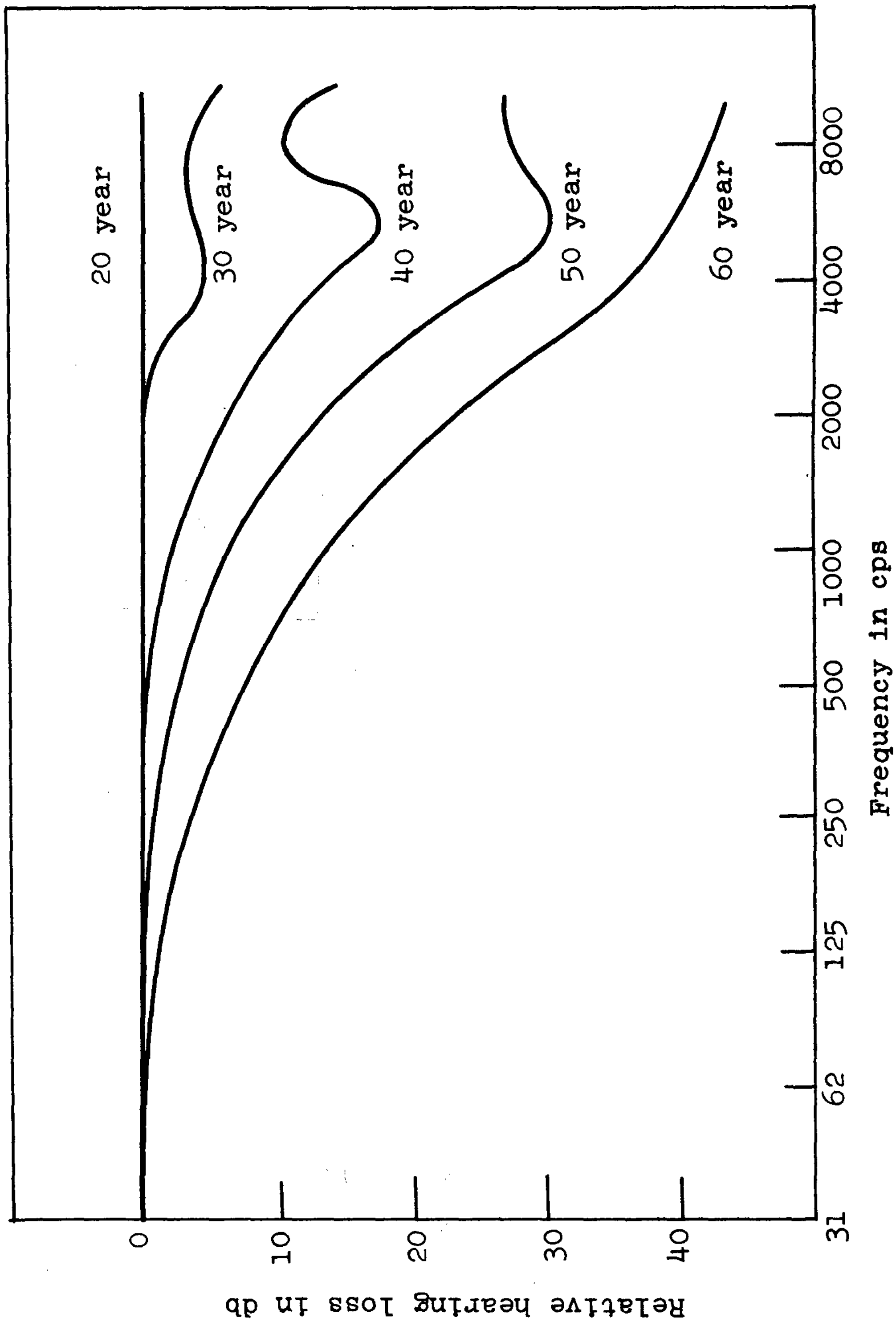
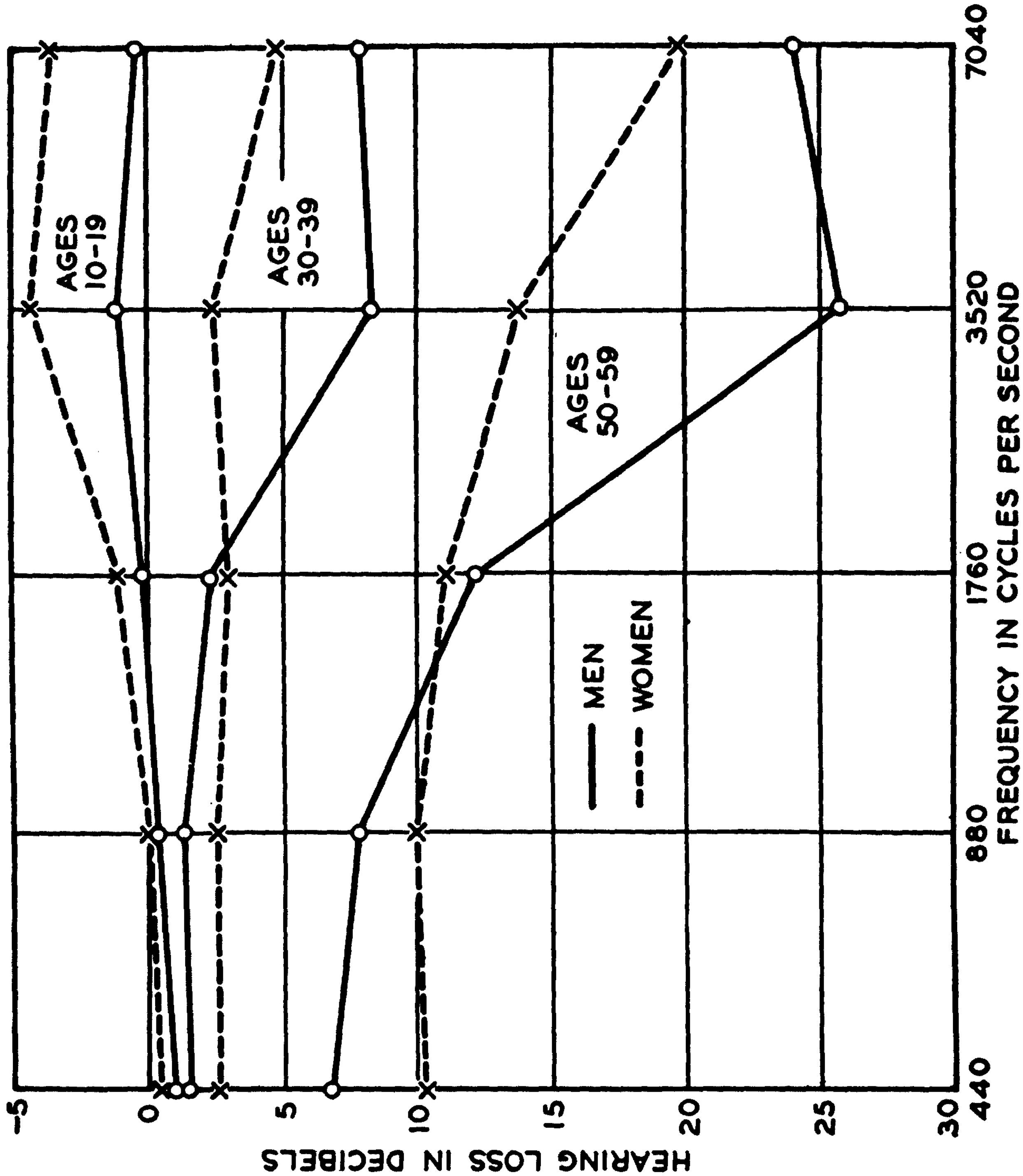
Figure 16.21

Progressive hearing loss with increasing age, as reported by Bunch 90/. The audiogram at 20 years of age is taken as a basis of comparison (From Morgan 91/).


20 year
30 year
40 year
50 year
60 year
0
10
20
30
40
Relative hearing loss in db
31
62
125
250
500
1000
2000
4000
8000
Frequency in cps


AGES
10-19
AGES
30-39
AGES
50-59
MEN
WOMEN
HEARING LOSS IN DECIBELS
-5
0
5
10
15
20
25
30
FREQUENCY IN CYCLES PER SECOND
440
880
1760
3520
7040

be unable to hear the most intense tone presented. It would appear wise, therefore, to use the median values instead of the means if a measure of central tendency is desired. The median values have the advantage of not reflecting the fact that the stimulus values are truncated at both ends of the continuum. The medians are also insensitive to skewness of the distributions (See Sec. 2.2). The whole story, of course, is only told by giving the complete distribution of thresholds.

TABLE 16.2

COMPARISON OF THRESHOLD SOUND PRESSURE LEVELS (IN DECIBELS RE 0.0002 DYNE/CM^2) MEASURED AT SAN DIEGO AND WORLD'S FAIRS FOR THE 20-29 YEAR GROUP. THE SIVIAN-WHITE DATA ARE SHOWN FOR COMPARISON

	San Diego 20-29 Year Group		Range of Instrument at San Diego		Sivian-White	World's Fairs 20-29 Year Group
Frequency	Mean SPL	Median SPL	Min. SPL	Max. SPL	MAP SPL	Mean SPL
cps	db	db	db	db	db	db
440	34	34	21	81	16	29
880	22	20	16	76	8	22
1760	18	18	12	72	6	18
3520	21	18	11	71	8	20
7040	22	18	9	69	16	22

Figure 16.22

Mean hearing loss in db for men and women in the 10-19, 30-39 and 50-59 year age groups. The data were taken at the World's Fair hearing tests. (From Steinberg, Montgomery and Gardner 5/).

We are including these details in a discussion of the problem of threshold versus age to illustrate three points: (1) one encounters numerous difficulties in obtaining what might be termed a "normal audiogram," i.e., a reference level that one can use in non-laboratory situations; (2) it takes studies as carefully prepared and monitored as the Fair studies or the survey by the U. S. Public Health Service involving many subjects in order to obtain the measure of agreement that has been found*. Finally, (3) we wish to draw the attention of those who might make audiometric studies in the future (even if they involve only comparisons of pre-employment audiograms with after-exposure audiograms) to the precautions that should be taken and reported so that others can gain a picture of the reliability of their studies.

Let us now compare the binaural data of the San Diego Fair with the monaural data of the New York and San Francisco Fairs for all age groups. Both sets of data, as shown in Table 16.3, exhibit the same trends with respect to age except that the San Diego population has somewhat more acute hearing. This circumstance might be attributable to the binaural presentation of the stimuli. The only really appreciable reversal of this consistent superiority trend for the San Diego population occurs in the 20-29 year age group. We shall come back to this finding in Chapter 17 when the effects of exposure to noise upon hearing is discussed.

Other findings of the San Diego survey are: (1) hearing loss in db is not normally distributed for the population as a whole, for males and females separately, or for any given

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* Even then, it is possible for a 5 db difference such as the one found at 440 cps to occur. The authors of the San Diego survey believe that this discrepancy should be attributed to what they term "experimental error."

Figure 16.23

Articulation score for three different types of speech material plotted as a function of relative intensity. (From Hudgins et al 95/ and Hirsh 19/).

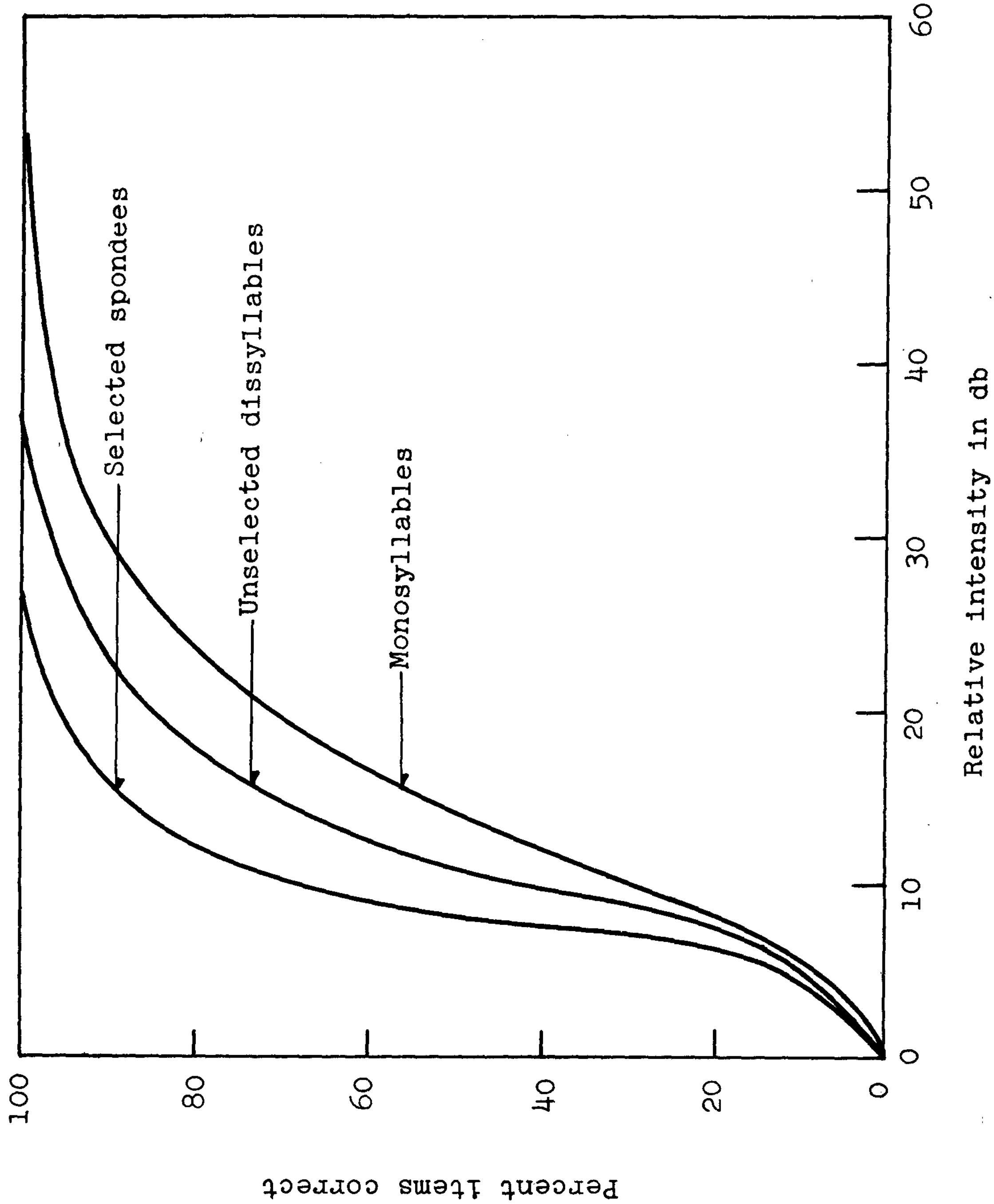
Selected spondees
Unselected dissyllables
Monosyllables
Relative intensity in db
Percent items correct
0
10
20
30
40
50
60
0
20
40
60
80
100

TABLE 16.3

COMPARISON BETWEEN MEAN HEARING LOSSES FOR THE SAN DIEGO COUNTY FAIR (SDF) AND WORLD'S FAIR (WF) POPULATIONS, FOR THE AGE GROUPS SHOWN. THE NUMBERS REPRESENT THE HEARING LOSS DETERMINED WITH RESPECT TO A "NORM", OR ZERO HEARING LOSS. THE NORM WAS SITUATED HALFWAY BETWEEN THE MEDIANS OF THE MALE AND FEMALE 20-29 YEAR AGE GROUPS AT SAN DIEGO

		Frequency 440		Frequency 880		Frequency 1760		Frequency 3520		Frequency 7040	
Age	Fair	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
10-19	SDF	-0.3	0.2	-1.0	-0.1	-1.9	-0.1	-3.2	-4.1	-3.3	-5.3
	WF	1.0	0.5	0.3	0.2	-0.3	-1.1	-1.2	-4.4	-0.4	-3.6
20-29	SDF	-1.3	-1.3	-0.7	0.7	0.4	-0.4	3.8	-3.8	3.9	-3.9
	WF	0.0	0.0	-0.2	0.2	-0.1	0.1	2.0	-2.0	1.5	-1.5
30-39	SDF	0.3	3.6	1.3	3.1	2.2	2.7	7.7	-0.7	6.5	-0.1
	WF	1.4	2.6	1.3	2.6	2.3	2.9	8.2	2.4	7.7	4.8
40-49	SDF	1.3	5.3	2.4	4.3	6.0	5.2	13.2	0.7	13.3	3.6
	WF	3.7	6.0	4.5	5.8	7.0	6.7	17.7	7.8	16.8	11.9
50-59	SDF	4.2	6.9	4.9	7.3	11.9	10.4	25.0	7.3	27.9	12.2
	WF	6.8	10.3	7.7	9.8	12.1	11.0	25.6	13.8	24.0	19.7
Over 60	SDF	7.0	9.5	9.0	9.0	19.3	14.8	33.5	15.6	36.1	23.3

ten-year grouping. Absolute hearing loss, as well as its dispersion and skewness, increases with age and frequency, (2) individual differences in hearing, as measured by the difference in hearing loss between the 5th and 95th percentiles of the population increase from 15 db for people under 30 at 880 cps to over 50 db (limit of this test) for the older age groups and for the higher frequencies.

When all these data are considered and when some of the evidence that has a particular bearing upon the relation of hearing acuity to exposure to noise is examined (see Sec. 17.4), we ask ourselves the question: do we have enough reliable information to establish a baseline for hearing acuity in various age groups that is reasonably uncontaminated by some of the factors whose effect we might want to assess?

Our answer can be only a qualified yes. There is more agreement than disagreement between these data, but we are still faced with a certain number of uncontrolled variables. We should certainly like to know about the individual's otological history and status, i.e., we should like to be able to separate out those whose hearing loss is attributable to an identifiable medical etiology.

We should also like to know more about the relation between the "normal audiogram" and the threshold curves that one can obtain in the laboratory. What factors account for the 10-15 db differences*? Is the difference attributable to practice, temporary hearing loss due to previous exposure, masking, or a combination of all three? We would feel better if we could show that a normal population will reach the Sivian and White values if the necessary precautions are taken. The present data represent a starting point. We now need to refine them. We need a study in depth (including repeat audiograms to test for reliability) that will take into account all the factors that the past has shown to be important.

In the meantime we shall have to base our estimates of the effects of exposure to noise upon the difference between

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* In the younger age groups tested at the San Diego Fair about 5% of the population were from 5 to 10 db better than 0 db hearing loss.

the population that is being studied and the above mentioned "baselines," unless the study includes its own control group 89/.

The preceding discussion of what has been called "presbycousis," that is, the variation of the thresholds for pure tones with age, by no means exhausts the effects of age upon performance in response to acoustic stimuli. However, so little data exists on other effects that we are unable to make even qualitative statements concerning most of them.

Recently, however, another aspect of man's behavior in response to acoustic stimuli has been measured as a function of age 93/. Subjects were instructed to release the index finger from a telegraph key at the sounding of a loud click. The mean reaction time for the age group between 18 and 39 years was measured as 122 milliseconds, while the 65-75 year age group (59 subjects) was 145 milliseconds. It is, however, worth stating that individual differences as well as variability in a given individual increases strikingly with age. This fact is dramatically underlined by the finding that 32% of the 65-75 year age group and 15% of the 76-86 year age group have faster reaction times than the average for the 18-39 year group.

Relation of Hearing Loss to Measures of Auditory Performance Other Than the Threshold. We have indicated that reduced auditory performance is usually measured in terms of a rise in the threshold for pure tones or for speech. It must not be assumed, however, that auditory functions other than absolute thresholds are not also modified. For example, just noticeable differences discussed in Section 16.2 have been shown to be affected, as has the accuracy with which people localize sounds. Ability to discriminate and to localize sounds is certainly of some importance to us in the performance of our tasks and in our social life.

Equal loudness contours and loudness functions for individuals with non-conductive type hearing loss (see next section) differ markedly from the corresponding functions for the normal population. For such individuals, an elevation in the absolute threshold for pure tones does not mean that the equal loudness contours are simply all shifted upwards by a fixed amount. On the contrary, at high stimulus intensities the loudness contours

may be quite normal*. The shape of the function relating loudness to stimulus intensity often provides information concerning the type of hearing loss encountered.

Types of Hearing Loss 19,102/. It has been customary in the past to recognize two fundamental kinds of hearing loss or deafness: "conductive" hearing loss and "perceptive" hearing loss. The two types may also exist in combination to provide a "mixed" type of hearing loss. Typical audiograms for persons with conductive, perceptive, and mixed loss are shown in Fig. 16.24.

Conductive hearing loss reflects a decreased sound transmission to the sensory endings in the inner ear. The ossicular chain, the eardrum and even the ear canal (wax) may be involved in this increased transmission loss. This type of deafness is usually characterized by a pure-tone hearing loss that is the same order of magnitude at all frequencies (see Fig. 16.24).

The maximum amount of conductive hearing loss is usually not more than 50 or 55 db. There clearly must be a limit to the transmission loss measured for air conducted sound since energy can still reach the inner ear by transmission through the bones of the head, even when there is no transmission along the normal air conduction route. In fact, the audiogram for bone-conducted sounds is usually about the same for individuals with conductive hearing loss and for individuals with normal hearing. Conductive hearing loss affects not only the threshold but also loudness functions. Curve C in Fig. 16.25 illustrates the modifications of an idealized loudness function under the hypothesis of constant transmission loss.

Conductive hearing loss reduces the intelligibility of speech, if the speech stimulus is presented in the quiet at low intensities. However, in many situations we are required to carry on a conversation in the presence of a masking noise, and we must raise our voices in order to make ourselves understood. The level of both the speech and the noise transmitted to the ear will be reduced for an individual with conductive hearing loss, but the relative levels, i.e., the signal-to-

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* For a more detailed discussion of the phenomenon of "recruitment", see Fowler 97/, de Bruine-Altes 98/, Lüscher and Zwislocki 99/, Huizing 100,101/ and Hirsh 19/.

noise ratio, will remain unchanged. Since the speech level is fairly high, the intelligibility is not limited by the threshold of hearing, but is limited by the level of the masking noise. Thus a person with conductive deafness will perceive speech in a sufficiently noisy environment about as well as a person with normal hearing.

Certain authors have indicated* that there is a reduction in intelligibility at constant signal-to-noise ratio if both signal and noise are sufficiently intense (about 100 db SPL). If these findings are correct, they would point to an advantage possessed by individuals with conductive deafness. For these individuals, the level of both speech and noise is reduced, but the signal-to-noise ratio remains constant. Consequently the intelligibility of speech in high-intensity noise would be improved in much the same manner as for individuals wearing earplugs.

Perceptive hearing loss is often referred to as nerve deafness. Nerve deafness is presumably related to degeneration of some of the sensory cells in the inner ear or to some similar process in the auditory nerve. The hearing loss for pure tones is usually different for diverse frequencies. High-frequency

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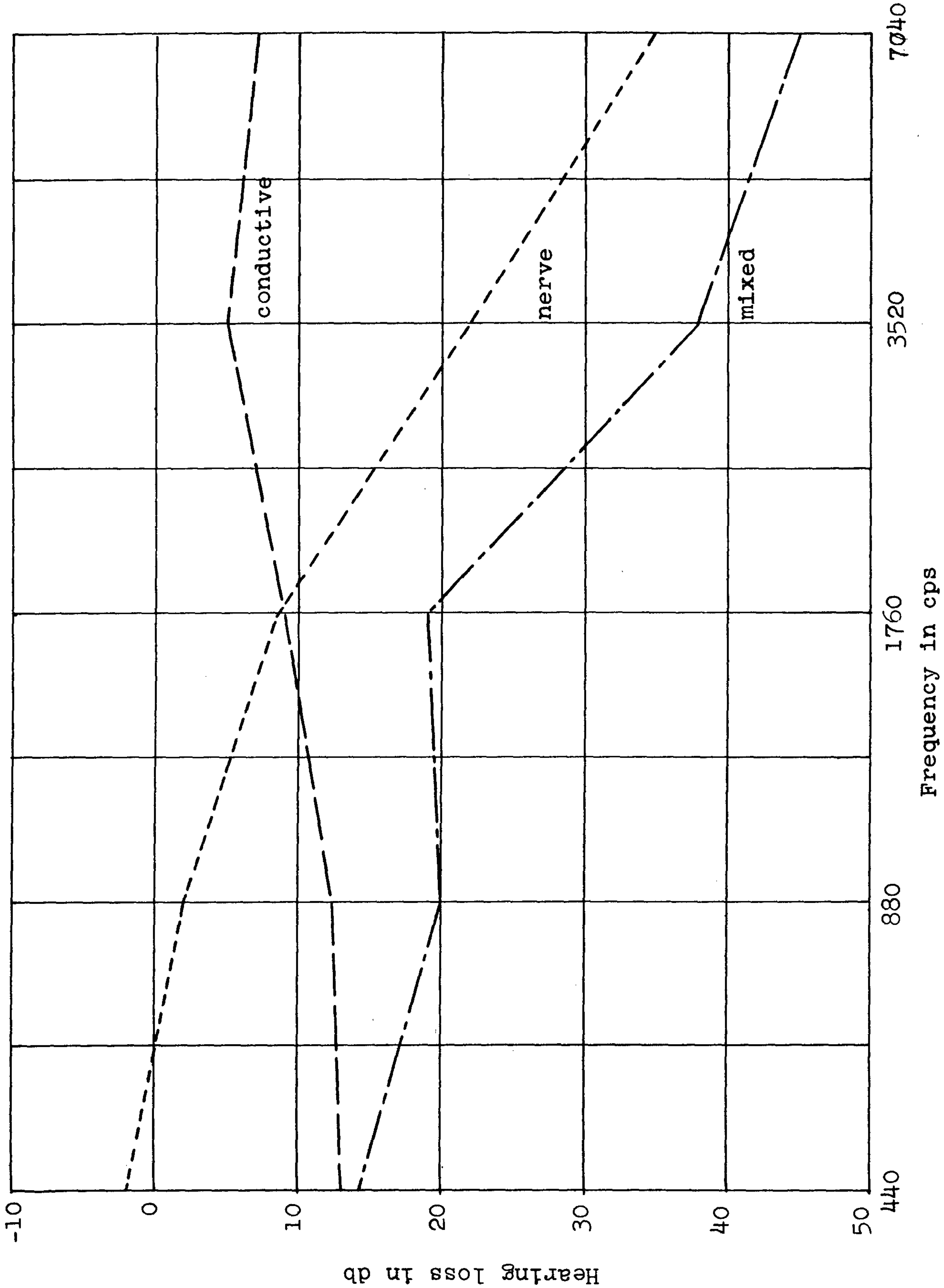
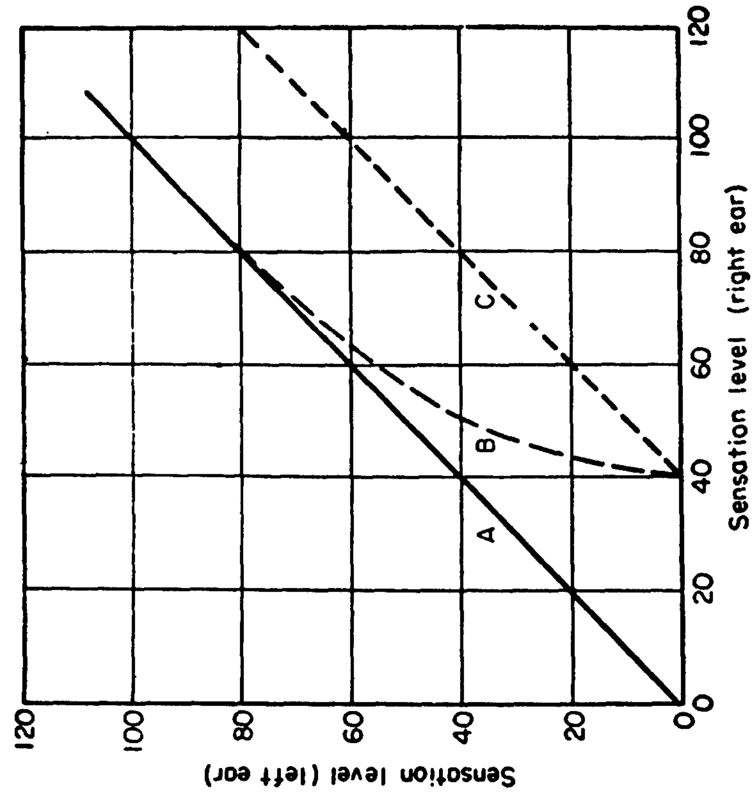
* See Figure A2.2, Appendix 2.

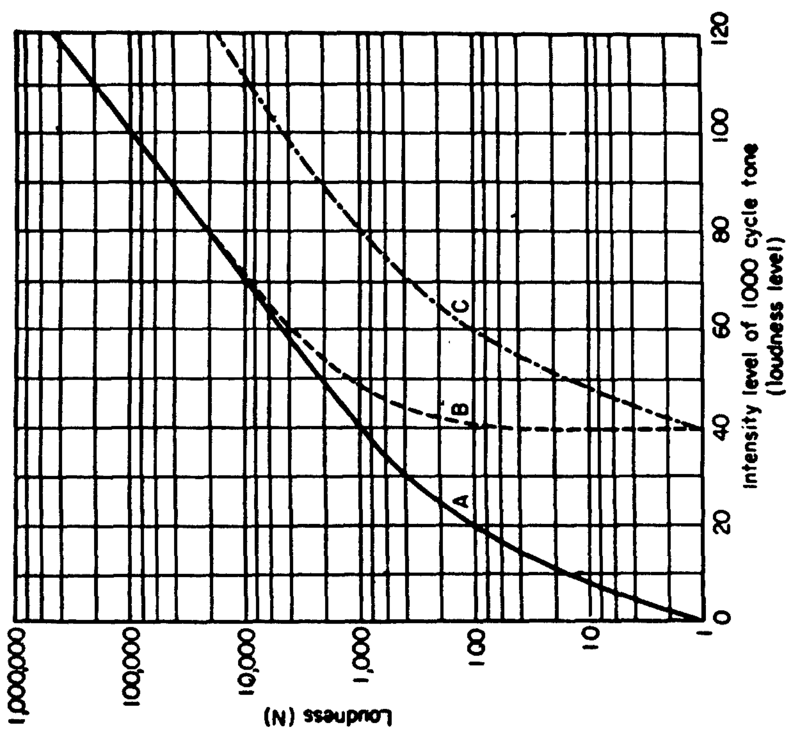
Figure 16.24

Median absolute hearing losses for various types of deafness groups measured at the San Diego County Fair. The following criteria were used in selecting the groups: (1) nerve deafness group, no greater than 6 db hearing loss (HL) on 440, no less than 1 db HL on 7040 provided the loss on 7040 was at least 24 db greater than that on 440; (2) conductive deafness group, at least 7 db HL on 440, any loss on 7040 provided the loss on 7040 is no more than 4 db greater than the loss on 440; (3) mixed deafness group, at least 7 db HL on 440, at least 21 db HL on 7040 provided the loss on 7040 exceeds the loss on 440 by 14 db or more. These criteria are, of course, arbitrary, and could be open to dispute by some medical groups. (After Webster et al 103/).


conductive
nerve
mixed
440
880
1760
3520
7040
Frequency in cps
-10
0
10
20
30
40
50
Hearing loss in db



Sensation level (right ear)
Sensation level (left ear)
0
20
40
60
80
100
120
A
B
C



Intensity level of 1000 cycle tone (loudness level)
Loudness (N)
1
10
100
1,000
10,000
100,000
1,000,000
0
20
40
60
80
100
120
A
B
C

tones are the ones most likely to be affected as indicated by the typical audiogram in Fig. 16.24. The audiogram illustrating nerve deafness shows a relatively gradual increase in hearing loss with frequency. Often, however, the transition is rather abrupt. Hearing losses encountered in industrial populations exposed to sounds of abnormally high intensities resemble those defined as nerve or perceptive losses.

Since the hearing loss at high frequencies is often quite large, an individual who is nerve deaf may not hear the high-frequency components of a stimulus regardless of the stimulus intensity. For example, the high-frequency sounds of speech would be inaudible, and the understanding of speech would be impaired. The listener must rely entirely on the speech components at lower frequencies to make his discriminations between speech sounds. The presence of a masking noise in this low-frequency range would impair his ability to make these discriminations, and his understanding of speech would therefore deteriorate rapidly.

Reference has been made above to the loudness contours and loudness functions for persons with non-conductive hearing loss. From the audiograms of Fig. 16.24 it is clear that faint tones of high frequency may not be heard by the nerve deaf, whereas they are perfectly audible to the normal person. Certain nerve-deaf individuals have been shown to hear high-intensity, high-frequency tones just as loudly as "normals."

Figure 16.25

The figure on the left shows theoretical functions relating loudness to intensity level for these cases: (A) normal hearing; (B) 40 db hearing loss of the perceptive type with recruitment; and (C) 40 db hearing loss of the conductive type with no recruitment. (From Steinberg and Gardner 65/, and Hirsh 19/). The three theoretical loudness functions are redrawn at the right as they would appear as results of alternate binaural loudness matches. The three curves show the relation between sensation level on the left (normal) ear and sensation level on the right (pathologic) ear for equal loudness at several levels. All results are for one frequency. (From Hirsh 19/).

There is on a logarithmic scale rather abrupt transition from hearing little or nothing at all to hearing very well (see Fig. 16.25). This phenomenon, known as "recruitment" is often very annoying to individuals with non-conductive hearing loss. They may have difficulty understanding a person speaking in a low voice, but when he raises his voice to be understood, they complain that he is shouting too loudly at them. Recruitment is thus a feature that distinguishes at least certain types of nerve deafness.

16.4 Speech Communication

Some of the physical properties of the speech sounds generated by a talker are discussed in this section. In addition we shall consider procedures for the measurement of the intelligibility of speech. We shall also discuss the use of these procedures in evaluating the loss in intelligibility in the presence of various types of masking and distortion.

Acoustic Properties of Speech. The average speech power emitted by a speaker at a conversational level lies between 10 and 20 microwatts, when the power is averaged over a long time interval. The average power level is, therefore, 80 to 83 db, using the definition of power level given in Chapter 15 and in Sec. 2.1. When one talks as loudly as possible the power level may rise to 100 db; for whispered speech the power level may be as low as 40 db.

The average sound pressure level 30 cm directly in front of the speaker's lips is thus from 66 to 69 decibels at a conversational level. At low frequencies, the radiation of sound from the lips is approximately non-directional, but at frequencies above 1000 cps the directional effects become pronounced. The sound pressure level is then greatest on the axis directly in front of the lips, and decreases to a minimum directly behind the head.

When the speech power is averaged over a time interval that is short compared with the time interval taken by a syllable (about 0.2 sec), sizeable fluctuations in the level are observed as different speech sounds are uttered. For example, the power of the strongest vowel (o) is about 47 microwatts, whereas the weakest consonant (v) has a power of only 0.03 microwatts, on the average 83/. If the pauses between sounds are excluded, the speech power levels measured in 1/8-second intervals lie within a range of about 30 db 104/.

A plot of the cumulative level distribution in the 1/8-second intervals is shown in Fig. 16.26. On this plot the ordinate indicates the percentage of time the speech power is greater than the level defined by the abscissa.

The distribution of speech power with frequency (averaged over long time intervals) has been measured by several investigators 104,107,108/. The average speech spectrum for male talkers is shown in Fig. 16.27, in which the ordinate represents the sound pressure level for bands one cps wide measured at a distance of one meter from the talker's lips. The form of the cumulative level distribution in Fig. 16.26 has been shown to be valid for bands of speech as well as for the overall speech signal.

If the speech energy in different frequency bands is averaged over a time interval between 0.003 and 0.02 seconds, a more detailed picture of the changes in the distribution of speech energy as a function of time is provided. The above limits for time intervals are short when compared to the duration of an individual speech sound. A three-dimensional intensity-frequency-time representation is normally used 109, 110/ to display the data that are obtained. Figure 16.28 shows one such display in which frequency is plotted vertically and time horizontally, while variations in intensity are indicated by shades of gray. Portions of the intensity-frequency-time pattern are characterized by bars or formants that change their frequency positions as different sounds are uttered. These formants denote resonances of the vocal tract similar in nature to the resonances of an organ pipe. As the vocal tract assumes new positions in the production of different vowel sounds the resonance pattern is changed. The impulsive and noise-like quality of the consonant sounds is also observable on the intensity-frequency-time pattern.

Articulation Testing Methods. In many applications the presence of unwanted masking noise or some other distorting influence modifies the speech signal that reaches the ears of a listener and impairs his ability to interpret correctly all speech sounds. A quantitative measure of the efficiency of speech communication must be established in order to evaluate the deleterious effects of the distortions.

The efficiency of a speech communication link* is usually evaluated by articulation testing methods 96/ although other procedures have been used occasionally in the past. A talker at the input to the communication link reads a sequence of test items which may be syllables, words or sentences. At the output, a listener is supposed to record the test items to the best of his ability. The percentage of correctly recorded test items is the articulation score.

For a given communication link the articulation score depends on the type of test material used 111/. The scores for digits and for sentences are higher than the scores for isolated words, which in turn are higher than the scores for nonsense syllables. Figure 16.23 in Section 16.3 has illustrated the marked differences in articulation scores that are obtained for selected spondees, unselected dissyllables and monosyllables. Articulation scores for three different types of test material are shown in Fig. 16.29. Scores for digits, words in sentences and nonsense syllables masked by white noise are plotted as a function of the signal-to-noise ratio.

A word spoken in isolation may not be correctly interpreted by a listener if some distortion or noise is present. However, the same word occurring in a sentence may be correctly recorded by the listener since additional information to assist

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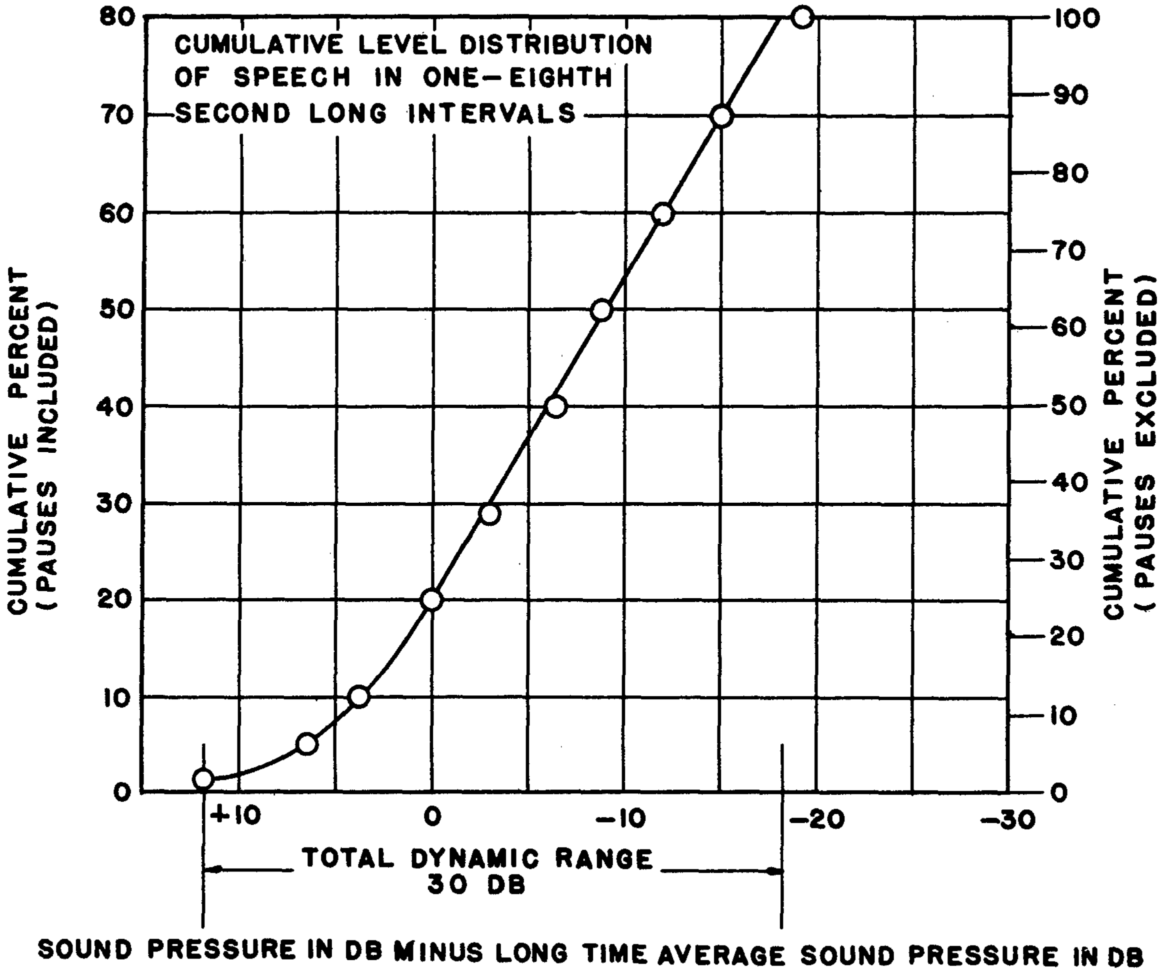
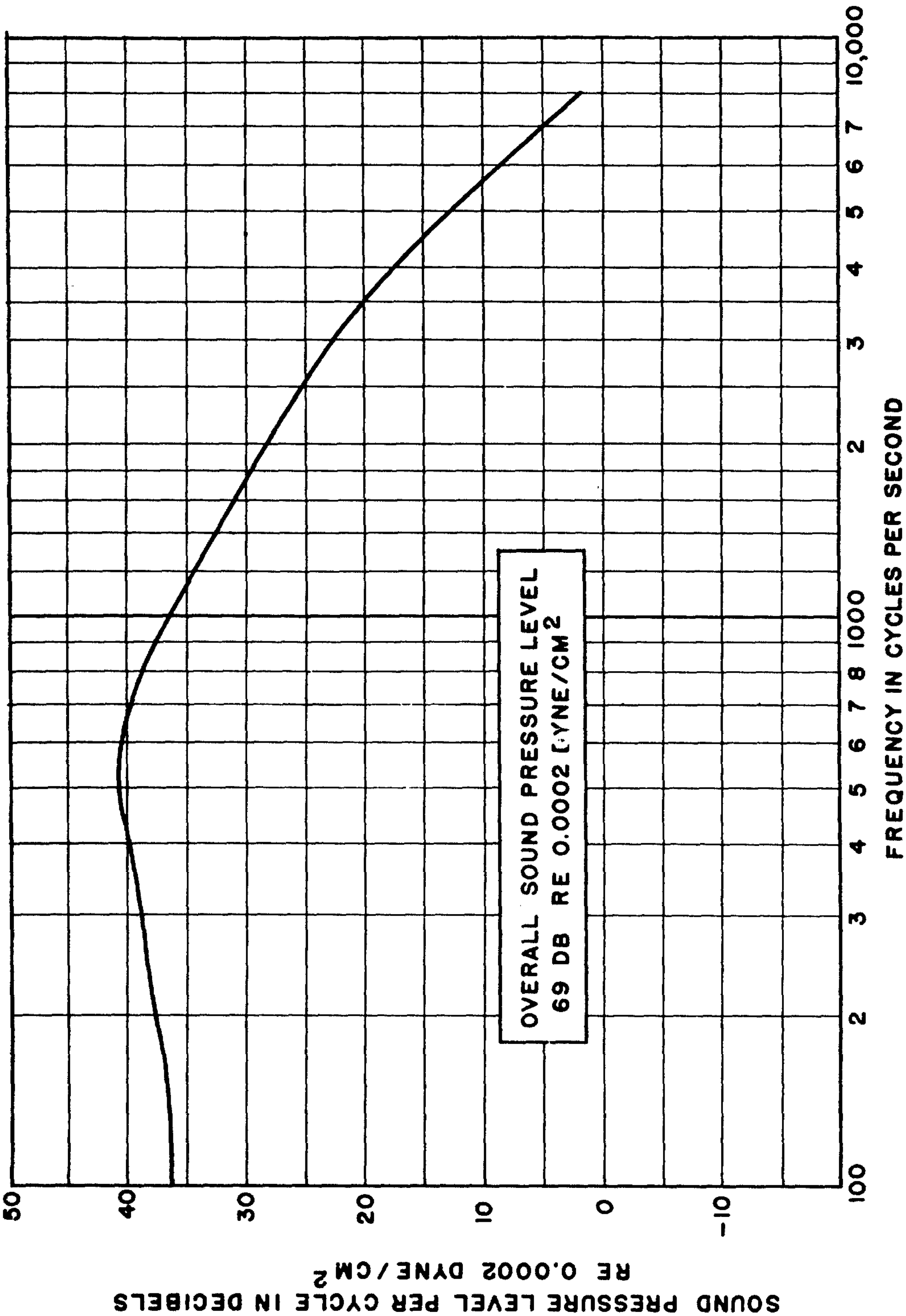
* The speech communication link may be simply an air path from the talker's mouth to the listener's ear or it may be a complex system with amplifiers, microphones, loudspeakers, or other components.

Figure 16.26

Cumulative level distribution of speech in one-eighth second long intervals. The abscissa represents the SPL measured in eighth-second intervals relative to the long time average SPL in db. The left-hand ordinate gives the cumulative percent of the time the level is greater than the level indicated by the abscissa. If the pauses in speech are excluded, the right-hand ordinate is to be used. (After French and Steinberg 105/, and Beranek 106/).



CUMULATIVE LEVEL DISTRIBUTION
OF SPEECH IN ONE-EIGHTH
SECOND LONG INTERVALS
CUMULATIVE PERCENT
(PAUSES INCLUDED)
CUMULATIVE PERCENT
(PAUSES EXCLUDED)
80
70
60
50
40
30
20
10
0
100
90
80
70
60
50
40
30
20
10
0
+10
0
-10
-20
-30
TOTAL DYNAMIC RANGE
30 DB
SOUND PRESSURE IN DB MINUS LONG TIME AVERAGE SOUND PRESSURE IN DB


OVERALL SOUND PRESSURE LEVEL
69 DB RE 0.0002 DYNE/CM^2
FREQUENCY IN CYCLES PER SECOND
100
1000
10,000
2
3
4
5
6
7
8
SOUND PRESSURE LEVEL PER CYCLE IN DECIBELS
RE 0.0002 DYNE/CM^2
50
40
30
20
10
0
-10

in identification of the word is present in the text. Similarly, if the listener knows in advance that the word is drawn from a restricted vocabulary (one of the ten digits, for example), he is more likely to identify the word correctly. Miller, Heise and Lichten 111/ have made a detailed study of the effect of the context and of the size of the test vocabulary on the percentage of items recorded correctly in the presence of a given noise.

The experience of the talker and listener also influences the results and care should be taken to insure proper training of test personnel. These and many other practical details that must be considered in conducting articulation tests are discussed in detail by Egan 96/.

Effects of Distortion of Speech on Intelligibility. Speech waves may be modified artificially by many types of distortion 113/. Their amplitudes may be increased or decreased; the speech may be masked by random noise or by other signals. The speech may be passed through frequency-selective circuits; non-linear distortion such as peak clipping may be applied to the speech wave; or various time distortions such as flutter or compression or expansion of the time scale may be introduced. Only the first four of the above types of distortion will be considered in this chapter. The others are of interest only in specialized situations not normally encountered in noise control.

The Intensity of Speech. When the talker and the listener are linked by a communication system that contains an amplifier with a variable gain (or when the distance between talker and listener in a free field is variable) the intensity of the speech reaching the listener may be readily controlled and the

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Figure 16.27

Average spectrum level of speech measured in one-cycle bands for young male voices talking at a level six decibels below the maximum they could sustain without straining their voices. Microphone placed one meter in front of talkers in an anechoic chamber. One decibel has been added to remove the effect of pauses between words in the total spectrum level. (After Clark et al 108/ and Beranek 106/).

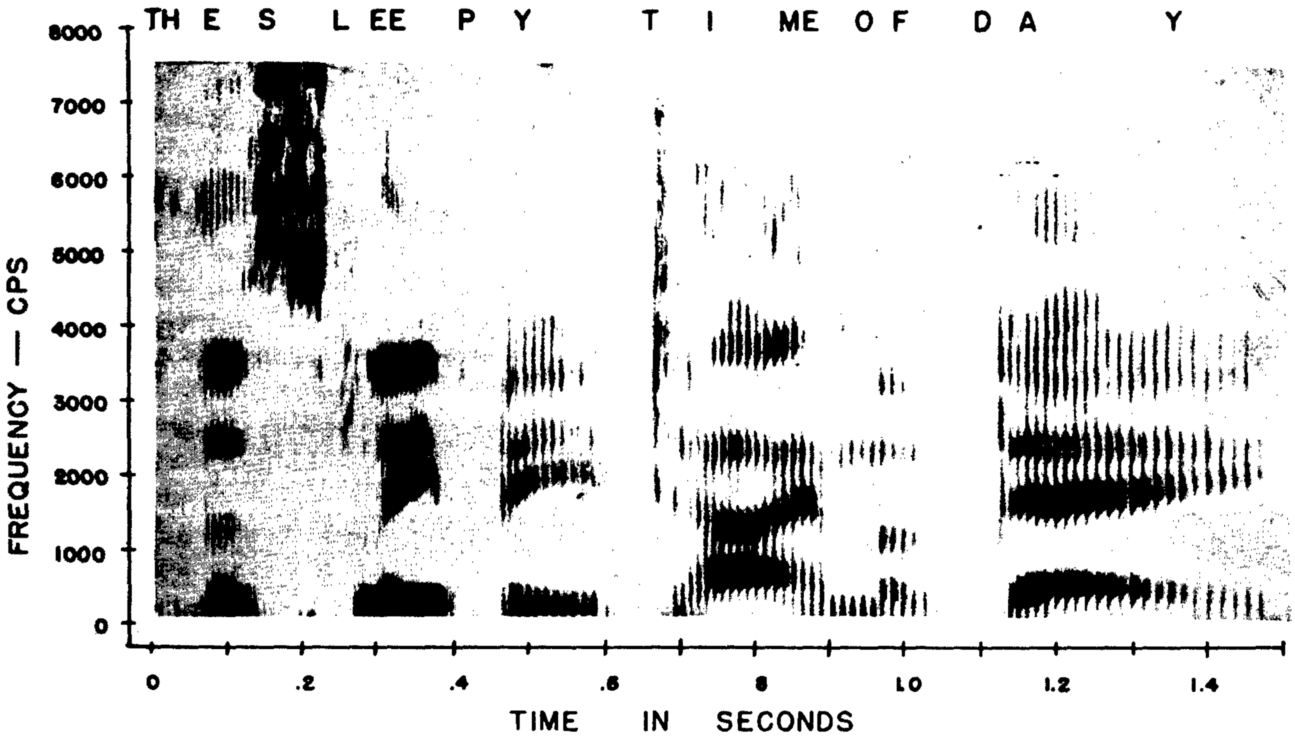

Figure 16.28

An intensity-frequency-time representation of the speech sample: "the sleepy time of day". Frequency is plotted vertically, and time horizontally. A concentration of energy in the speech signal at a given frequency and time is depicted as a darkening at the corresponding point in the pattern. The amount of darkening depends upon the intensity. For the vowel sounds, the resonances show up as horizontal bars on the pattern. High-frequency energy concentrations typify such consonants as [s] and [t].

articulation score as a function of intensity may be measured. As the gain of the amplifier is increased from zero the listener at first reports the presence of the speech signal. The presence of about half the words can be detected when the sound pressure level of the speech is about 5 db re 0.0002 dyne/cm^2. The articulation score increases gradually from zero as the speech intensity is increased above the threshold of detectability (Fig. 16.30). The rate of increase depends upon the type of test material (see Fig. 16.23). Eventually the intensity is sufficiently high that almost all test items are recorded correctly and the score remains close to 100 per cent until the threshold of pain is reached. At very high intensities there is sometimes a drop in articulation score with increasing intensity.

The Masking of Speech. In a great number of military and industrial situations individuals must talk to each other in the presence of sounds that mask speech and reduce its intelligibility. Several distinct types of masking noise are encountered. The masking noise may have a continuous spectrum, and may be continuous in time; it may have periodic components of one or more frequencies; or it may have an irregular or impulsive temporal characteristic.

Most laboratory investigations have used white noise (see definition in Chapter 15) as a masker. In such experiments articulation scores for several types of test vocabulary have been plotted (Fig. 16.29) as a function of the speech-to-noise ratio. As we have pointed out, the articulation score is higher both for words in sentences (in which the context furnishes additional clues) and for special test vocabularies containing fewer items, such as digits.

In most situations encountered in practice the spectrum of the masking noise differs from that of white noise. The intelligibility of speech masked by bands of noise has been measured by Miller 114/. His results are summarized in Fig. 16.31 for a fixed speech level of 95 db. They show that at low noise levels high frequency bands of noise are more effective maskers than are bands below 1000 cps. At high noise levels, however, the low frequency bands become more effective. This conclusion is illustrated clearly in Fig. 16.32, which is re-plotted from the data of Fig. 16.31.

In Miller's experiments the subjects wore earphones; the speech and masking noise were applied in phase to each phone. In recent years some attention has been directed toward the

influence of interaural phase in binaural perception. Hirsh, in particular, has shown that for pure tones in the range up to 1000 cps in the presence of strong noise, detectability of a signal depends critically upon the phase relations across the head 76,115/. We cannot go into the details of these studies here, but we would like to illustrate the effect by the following example.

Assume that we present to a subject a 200 cps tone over earphones in such a manner that the 200 cps sine waves are in phase opposition at the two ears. Then we turn on a noise whose overall SPL is near 100 db and we assume the noise to be the same at both ears. Hirsh measured the masked threshold under these circumstances and he found that it was about 5 db better (i.e. lower) than the monaural masked threshold for the same 200 cps tone. He now reversed the phase of the 200 cps tone in one ear so that the sine waves were now in phase at both ears. The phase relation for the noise was not altered. In this new situation the masked threshold was about 13 db worse than for the previous binaural presentation. In other words, two ears were now about 8 db worse than one. This effect is a function of the intensity of the masking noise.

Licklider 116/ has examined the effects of interaural phase in speech perception. He has shown that the phase relations of the speech and the noise at the two ears affect not only the masked threshold but also the articulation scores that are obtained for a given speech-to-noise ratio. For example, when either the speech waves or the noise waves at the two ears are 180° out of phase, word articulation scores are as much as 25 percent higher than when both the speech waves and the noise waves at the two ears are in phase. When two people converse in a room in which masking noise is present, the fact that they are able to localize the source of the speech by orienting their heads helps them. If the noise level is rather high they tend to turn one ear toward the source, thereby taking advantage of the decreased distance

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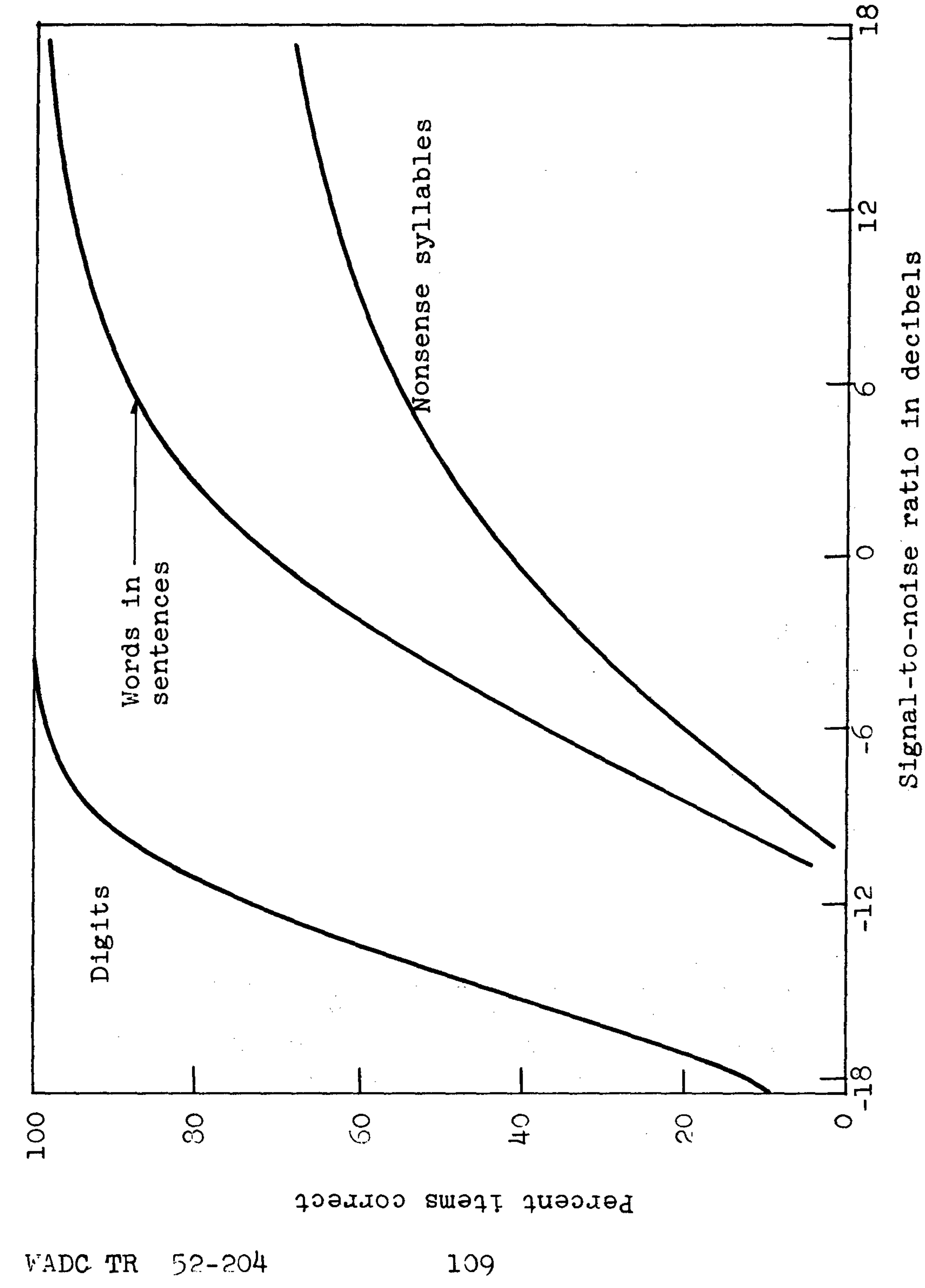
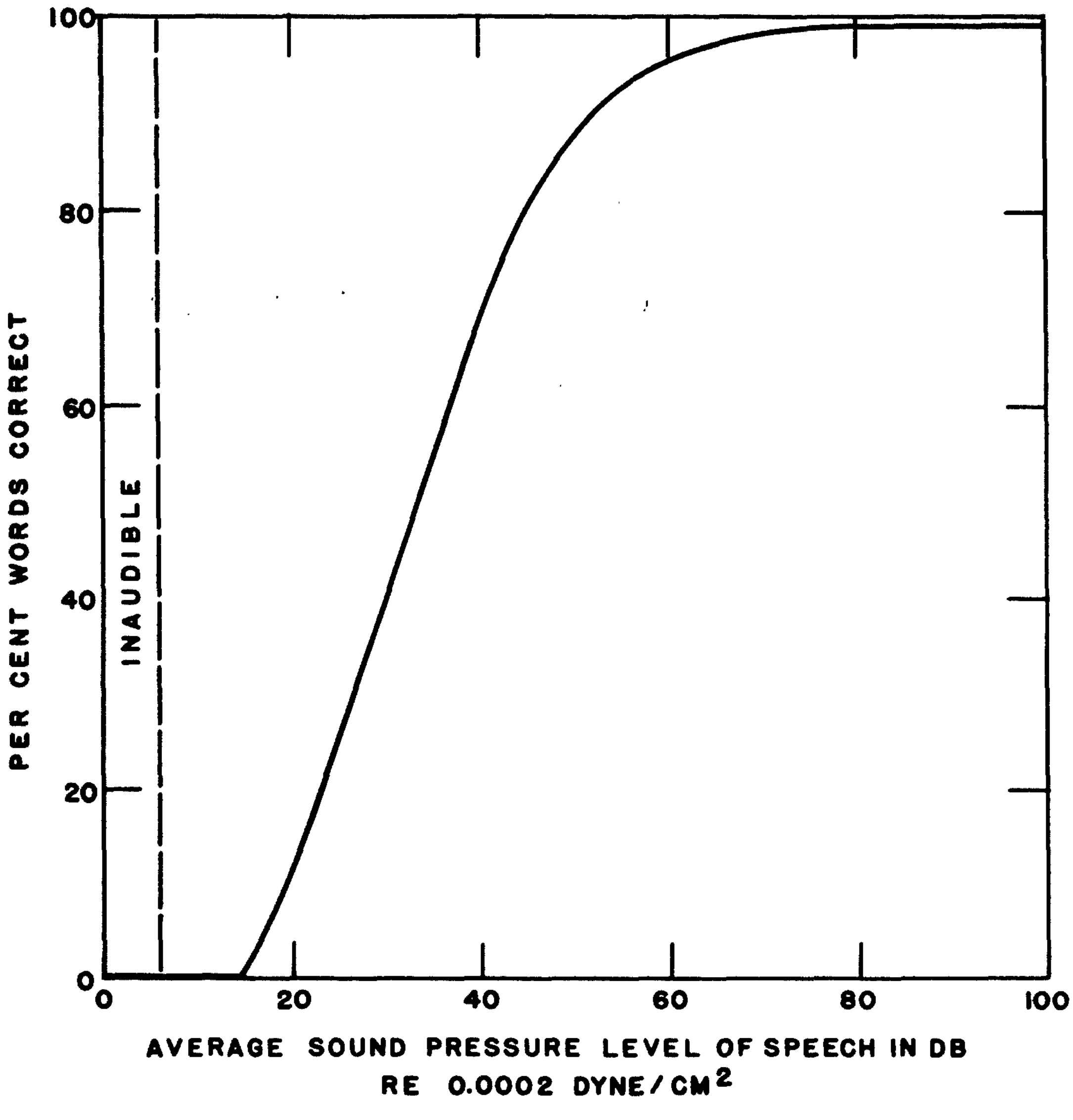
Figure 16.29

Articulation scores for three different types of test material. The test items were masked by white noise, and the percent items correct are plotted as a function of signal-to-noise ratio in decibels. (From Miller, Heise and Lichten 111/).


Digits
Words in sentences
Nonsense syllables
Signal-to-noise ratio in decibels
-18
-12
-6
0
6
12
18
Percent items correct
100
80
60
40
20
0


100
80
60
40
20
0
PER CENT WORDS CORRECT
INAUDIBLE
0
20
40
60
80
100
AVERAGE SOUND PRESSURE LEVEL OF SPEECH IN DB
RE 0.0002 DYNE/CM²

from the source to the ear and the interaural phase phenomenon at the same time. The most advantageous application of the interaural phase relation can be made for situations in which the ambient noise is high while the speech signal comes over a pair of earphones.

The threshold of perceptibility has been defined as the faintest level of speech at which the gist of connected discourse can be followed by trained listeners exerting continued effort. Stevens, Miller and Truscott 117/ have investigated the effects of pure and complex tones upon the threshold of perceptibility of speech. Figure 16.33 shows how sine waves, square waves and pulses mask speech. In these curves 117/ the masking is the difference in decibels between the threshold of perceptibility of the speech in the presence and in the absence of the masking signal. The relative effectiveness of the three types of masking signals may be compared because the relative levels of the masking signals are indicated in terms of the peak voltage impressed on the earphones. Sine waves of low frequencies mask speech more effectively than high frequency tones. Tones with frequencies between 300 and 500 cps are the most effective masking stimuli. Square waves and pulses mask speech somewhat more effectively than sine waves since they contain frequency components that extend over a wider range of frequencies. For frequencies above 1000 cps, however, sine waves, square waves and pulses are about equally ineffective in the masking of speech. In a subsequent section, we shall see some of the reasons why this is so.

The masking effectiveness of a noise is markedly dependent upon its temporal continuity. In general, the masking effectiveness is decreased if the masking noise is turned off periodically, but the magnitude of this decrease is dependent upon the fraction of time the noise is on and the number of interruptions per second. Results obtained by Miller and Licklider 118/ are summarized in Fig. 16.34. At slow rates of interruption between 1 and 100 per second, it is possible to patch together the bits of speech heard between the bursts of noise and, therefore, the masking effectiveness of such

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Figure 16.30

Articulation score for monosyllabic words as a function of the SPL of the speech. (From Miller 113/).

noises is rather low when compared with continuous noise. For interruption rates above 200 per second, the masking is effectively equivalent to that of continuous noise.

Frequency Selectivity. A different type of distortion occurs if speech is passed through a system that is selective with respect to frequency. If we remove portions of the speech spectrum by means of filters we can perform articulation tests on the remaining portions of the signal and evaluate the relative importance of different frequency bands to intelligibility. French and Steinberg 105/ have reported the results of articulation tests for both male and female speech signals passed through various high and low pass filters. Some of their data on syllable articulation are summarized in Fig. 16.35.

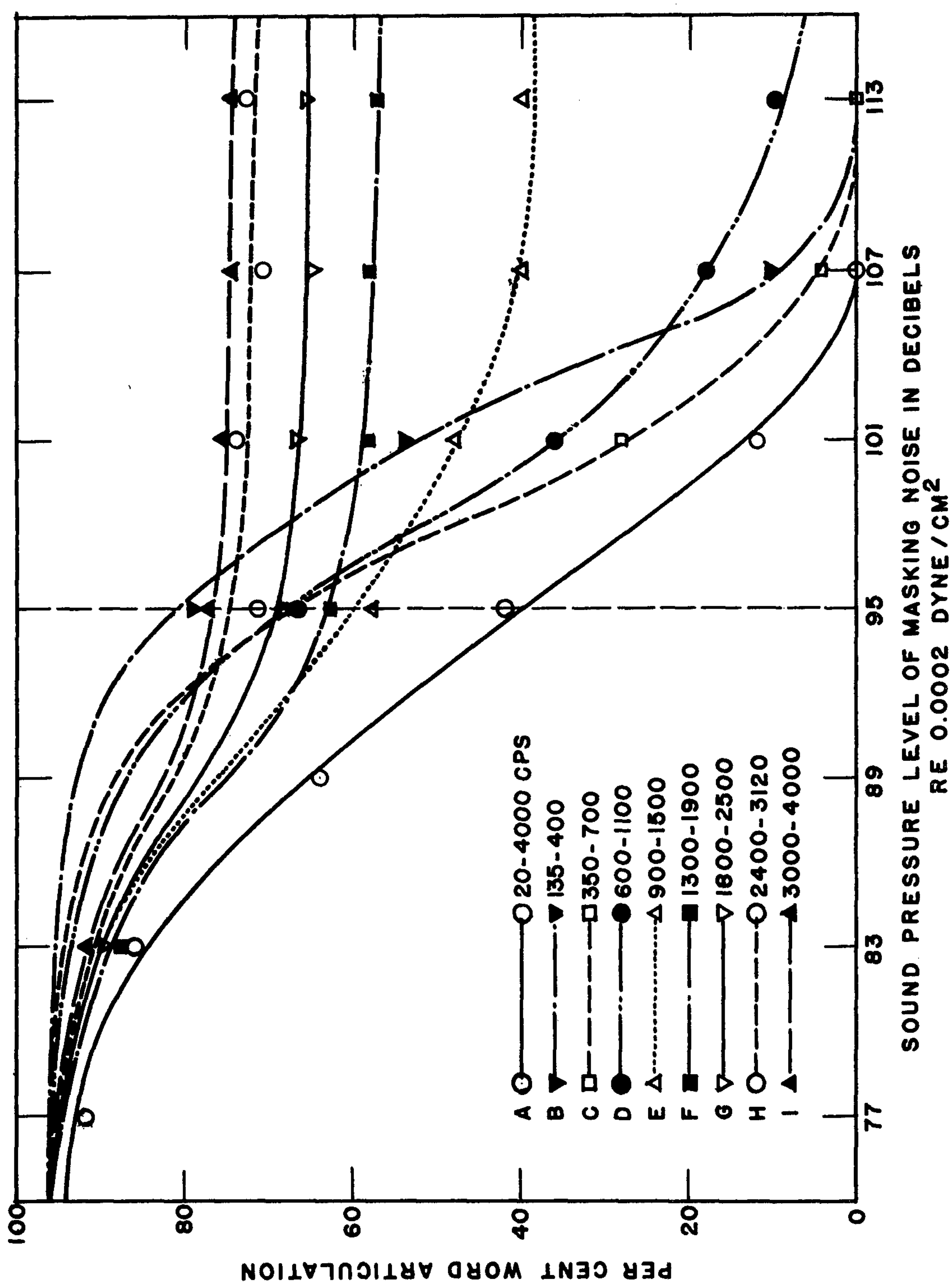
The data for low pass filters indicate that there is only a small increase in articulation score for cut-off frequencies above 5000 cps. A low pass filter with a cut-off frequency of 300 cps provides essentially an articulation score of zero. Likewise, a filter passing all frequencies above 300 cps gives an articulation score close to 100 percent.

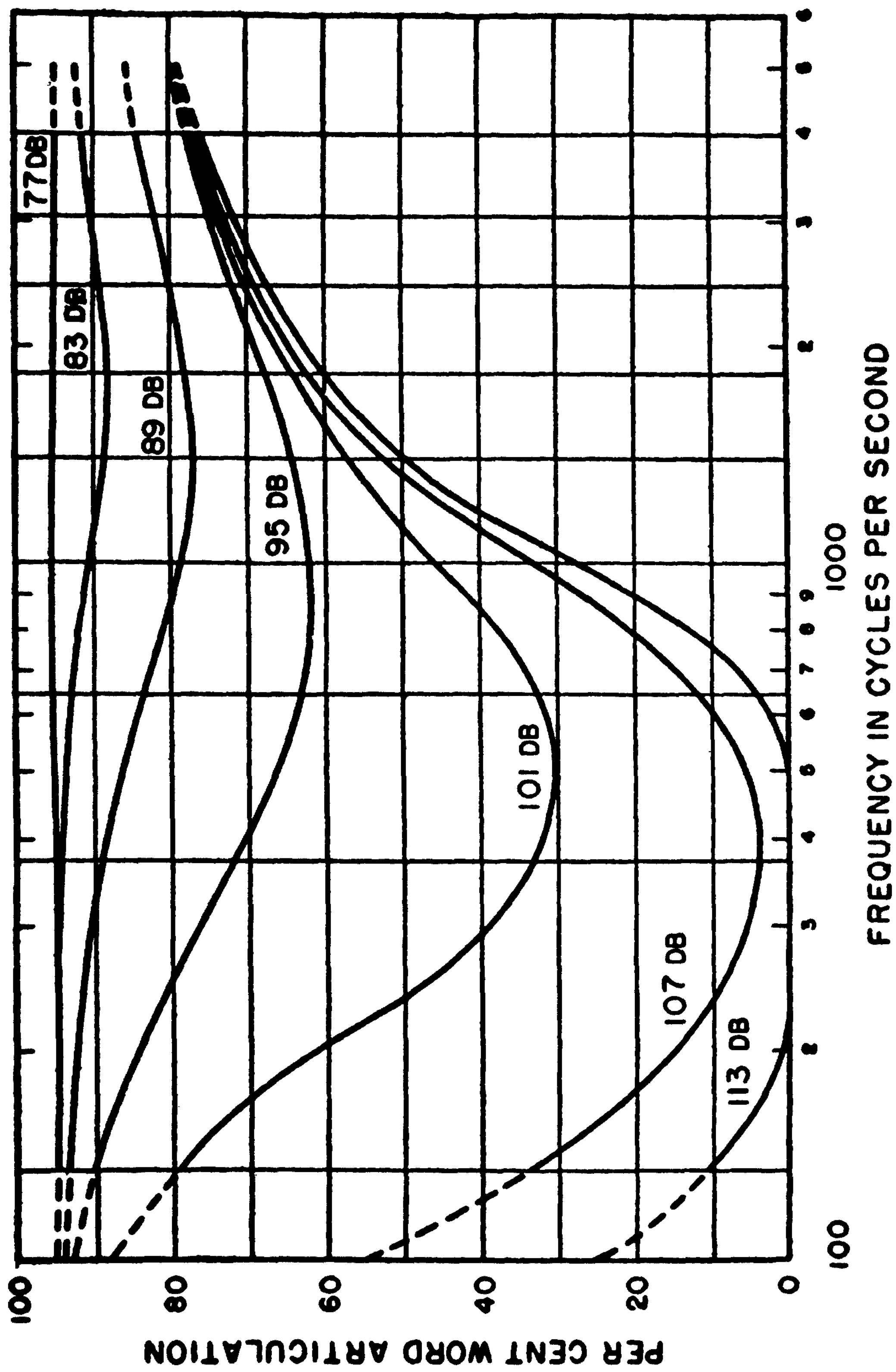
If we use the relation between syllable articulation and sentence articulation (see Fig. 16.29 for example) we see that a speech communication system passing either all frequencies below or above 2000 cps will, in the quiet, yield close to 100 percent sentence intelligibility. The speech will not sound natural but it will be intelligible, and in certain circumstances this may be all that is desired. Such a speech signal, having lost much of its redundancy, will prove more vulnerable to noise than a normal broad band signal.

The intelligibility of filtered speech masked by noise has been measured by Pollack 119/. Likewise, Egan and Wiener 120/ have studied the intelligibility of narrow bands of speech in the presence of noise. Pollack's data show that the relative contribution of the various speech frequencies to intelligibility in the presence of noise is not constant.

Figure 16.31

The articulation score for monosyllabic words as a function of the SPL of the masking noise. The different frequency bands of noise are parameters. The level of the speech was held constant at 95 db. (From Miller 114/).


PER CENT WORD ARTICULATION
SOUND PRESSURE LEVEL OF MASKING NOISE IN DECIBELS
RE 0.0002 DYNE / CM2
A 20-4000 CPS
B 135-400
C 350-700
D 600-1100
E 900-1500
F 1300-1900
G 1800-2500
H 2400-3120
I 3000-4000
0
20
40
60
80
100
77
83
89
95
101
107
113


77 DB
83 DB
89 DB
95 DB
101 DB
107 DB
113 DB
100
1000
FREQUENCY IN CYCLES PER SECOND
100
80
60
40
20
0
PER CENT WORD ARTICULATION

Rather the relative contribution is a function of the intensity of the speech signal relative to the constant white noise masking signal. As the SPL of the speech signal is increased, the relative contribution to intelligibility of the higher speech frequencies increases.

Amplitude Distortion. Amplitude distortion is commonly encountered in speech communication links that include non-linear components such as vacuum tubes and carbon microphones. When communication is via air path only, appreciable amplitude distortion is not encountered, but a study of the effects of amplitude distortion upon the intelligibility of speech contributes to our understanding of the process of speech perception.

Suppose the speech wave is passed through a device that limits the amplitude of the wave. Thus when the amplitude of the speech wave at the input is equal to or greater than a fixed amplitude, the output wave is limited in amplitude. The number of decibels by which the amplitudes of the peaks are reduced by limiting defines the amount of peak clipping. Infinite peak clipping would reduce the speech wave to a succession of rectangular waves. The output would switch polarity every time the speech wave crosses the time axis. Licklider 121,122/ has measured the percent word articulation for speech that has been subjected to various amounts of peak clipping. In his experiments he maintained a fixed peak-to-peak amplitude of the speech at the earphones. That is, the speech wave re-amplified after clipping in order to maintain the same peak-to-peak amplitude that existed before clipping. Licklider's results, shown in Fig. 16.36, indicate that a surprisingly large fraction of the speech wave can be eliminated before intelligibility is greatly affected. Even when the speech is reduced to a succession of rectangular waves, about 70 percent of the words can still be understood.

Figure 16.32

Smoothed curves drawn from the data of Fig. 16.31. The articulation score is shown as a function of the component frequencies of the masking noise. The parameter is the SPL of the masking noise. (From Miller 114/).

Pollack 124/ has measured the effect of frequency and amplitude distortion on the intelligibility of speech in noise. His data show that at low signal-to-noise ratios, the intelligibility of the clipped speech signal is considerably higher than that of the unclipped signal.

Articulation Index. It is often desirable to predict the intelligibility of speech passed through a speech transmission system without resorting to laborious articulation tests. On the basis of the results of laboratory articulation tests such as those described above, empirical relations between the articulation scores and the pertinent system parameters (such as masking noise, or frequency characteristics) have been derived.

Since the articulation score depends on the type of test material used, it is necessary to define a more fundamental measure of articulation efficiency. The definition of a new quantity, called the articulation index, will be illustrated in the following hypothetical experiment. Let us divide the audible frequency range into a number of contiguous frequency bands (say 10), with the width of each band adjusted so that the articulation score of speech when passed through each band at a normal intensity level is the same. The articulation index for each band is taken as 10, and the total articulation index for all bands is 100. Each band of speech is, therefore, assumed to contribute independently to the index so that the articulation index for several bands together is simply the sum of the indices of the individual bands. A relation of this type does not hold for the articulation score. For example, the word articulation score for the case of nine of the ten bands is about 98 percent, although the articulation index is 90. Experimentally determined relations between the

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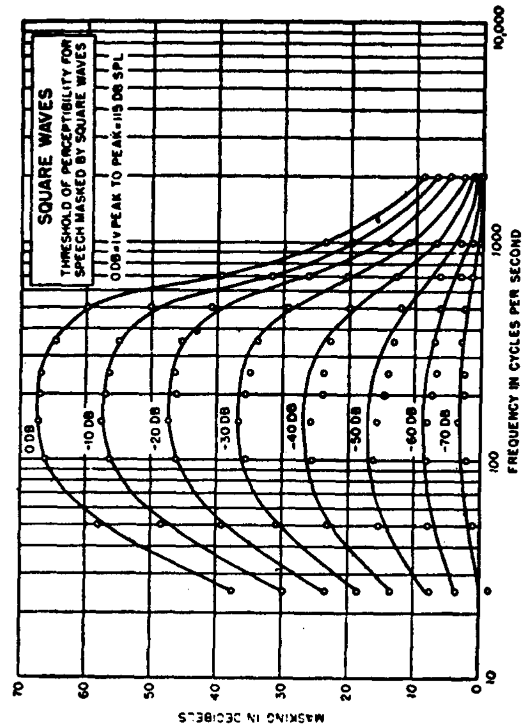
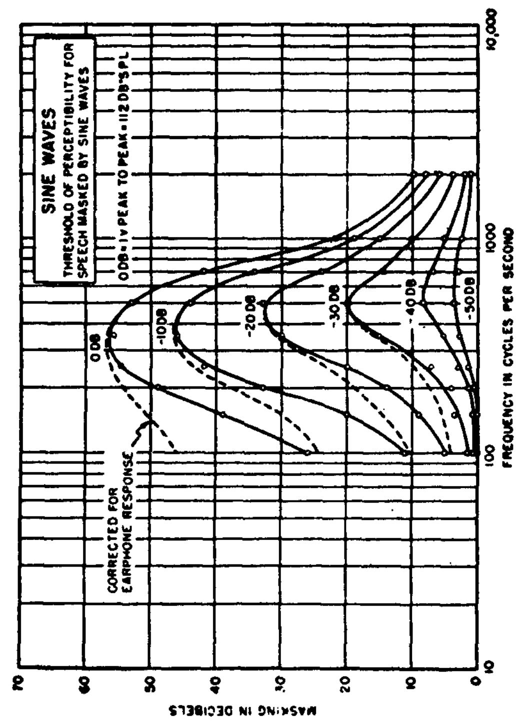
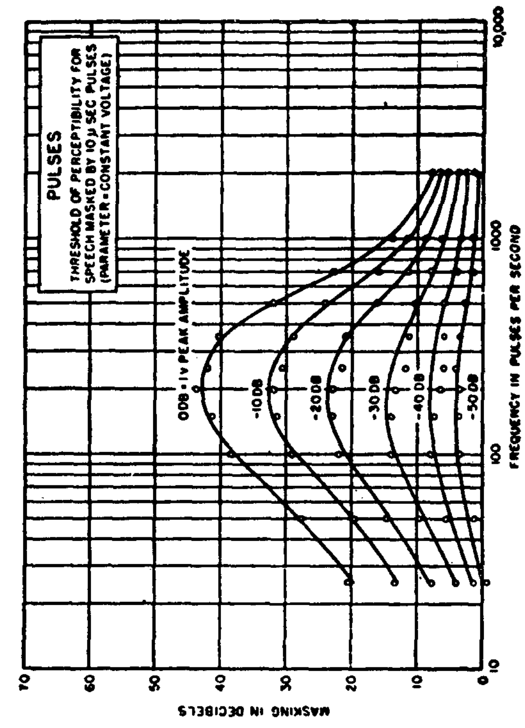
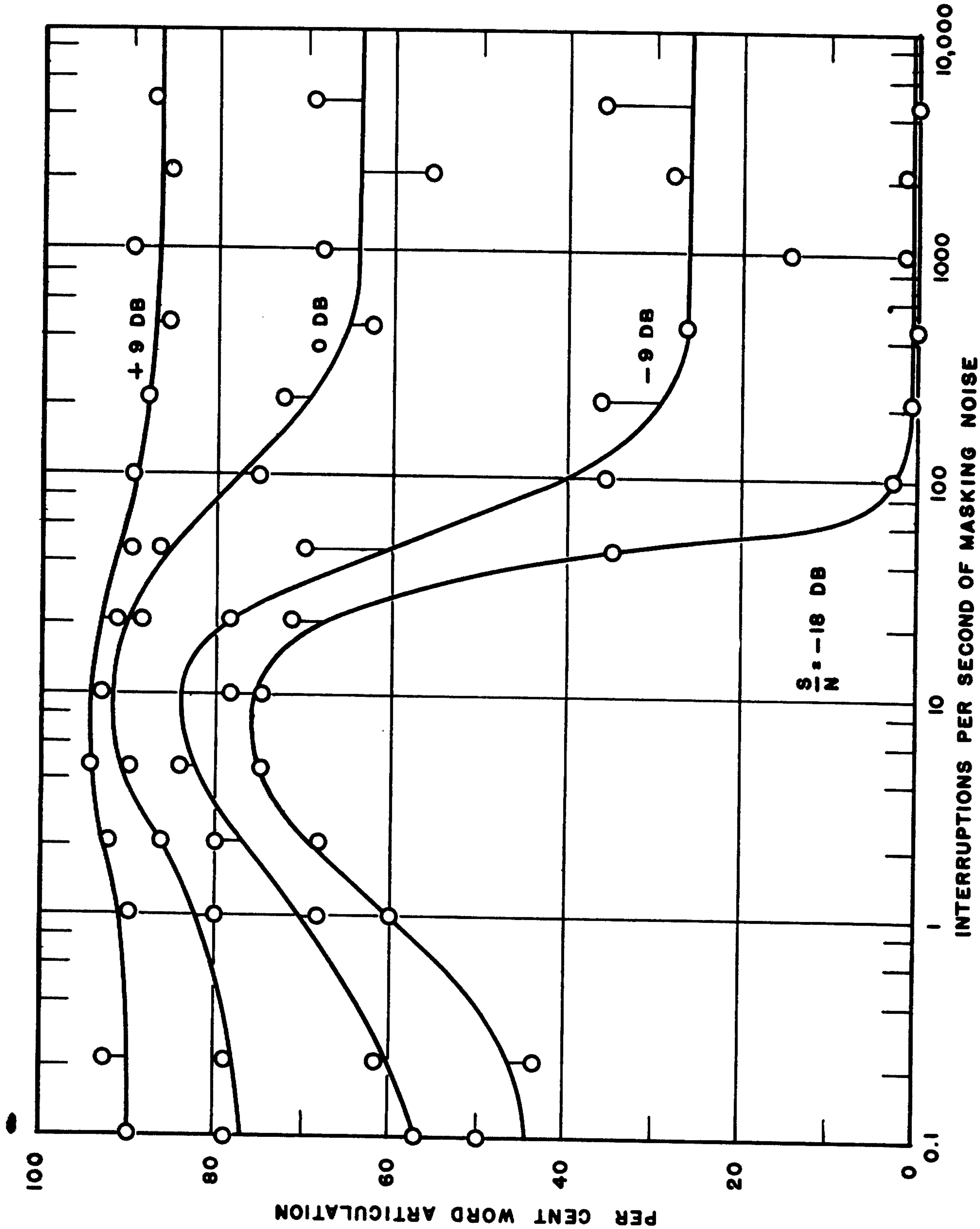
Figure 16.33

The masking of speech by sine waves, square waves and pulses. The ordinate shows the change in the threshold of perceptibility, or the masking. The peak voltage applied to the earphones for each masking signal was held constant at one volt for the curves labeled 0 db. For a sine wave, one volt peak to peak corresponds to a SPL of 112 db. All measurements were made binaurally (From Stevens, Miller and Truscott 117/)


SQUARE WAVES
THRESHOLD OF PERCEPTIBILITY FOR SPEECH MASKED BY SQUARE WAVES
0 DB = 1 V PEAK TO PEAK = 119 DB SPL
0 DB
-10 DB
-20 DB
-30 DB
-40 DB
-50 DB
-60 DB
-70 DB
MASKING IN DECIBELS
FREQUENCY IN CYCLES PER SECOND


SINE WAVES
THRESHOLD OF PERCEPTIBILITY FOR SPEECH MASKED BY SINE WAVES
0 DB = 1 V PEAK TO PEAK = 112 DB SPL
0 DB
-10 DB
-20 DB
-30 DB
-40 DB
-50 DB
CORRECTED FOR EARPHONE RESPONSE
MASKING IN DECIBELS
FREQUENCY IN CYCLES PER SECOND


PULSES
THRESHOLD OF PERCEPTIBILITY FOR SPEECH MASKED BY 10 μ SEC PULSES (PARAMETER = CONSTANT VOLTAGE)
0 DB = 1 V PEAK AMPLITUDE
-10 DB
-20 DB
-30 DB
-40 DB
-50 DB
MASKING IN DECIBELS
FREQUENCY IN PULSES PER SECOND



+9 DB
0 DB
-9 DB
S/N = -18 DB
INTERRUPTIONS PER SECOND OF MASKING NOISE
0.1
1
10
100
1000
10,000
PER CENT WORD ARTICULATION
0
20
40
60
80
100

articulation scores for several types of test material and the articulation index are shown in Fig. 16.37 105/.

When filtered speech is masked by noise the articulation index is decreased to an extent depending on the intensity level and spectrum of the masking noise. For masking noises that have a reasonably uniform and continuous spectrum level, the articulation index may be evaluated by procedures developed by French and Steinberg 105/, and Beranek 106/.

Let us focus our attention on one of the 10 bands of equal contribution to the articulation index. The intensity levels of the speech in this band vary during continuous speech over a range of about 30 decibels, and the cumulative distribution of levels measured on a decibel scale is approximately linear, as shown in Fig. 16.26. The noise in this frequency band will mask the speech by an amount depending on the level of the noise relative to the 30 decibel range. The assumption made by French and Steinberg and by Beranek, and supported by experimental articulation data, is summarized as follows: the contribution of the band to the overall articulation index is equal to the articulation index for the unmasked band multiplied by the fraction of the 30 decibel range that is not covered by the noise. Both speech and noise levels are measured in terms of decibels per cycle.

Beranek has summarized the above concepts of articulation index in the form of a chart, shown in Fig. 16.38. The normal, undistorted speech spectrum and the range of speech levels are represented by the shaded speech area. Adjustment of the gain or the frequency response of the speech communication link moves the speech levels (as a function of frequency) up or down on the decibel scale. The frequency scale is so selected that equal distances along this scale provide equal contributions to articulation index. If the spectrum level of a masking noise is plotted on the same chart, the portion of the speech

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Figure 16.34

Articulation scores for monosyllabic words were obtained in the presence of masking noise interrupted at various rates. The noise was on half the time, off half the time. The parameter is the signal-to-noise ratio in decibels. (From Miller and Licklider 118/)

area that remains unmasked by the noise spectrum represents the articulation index for the system in the presence of the given noise.

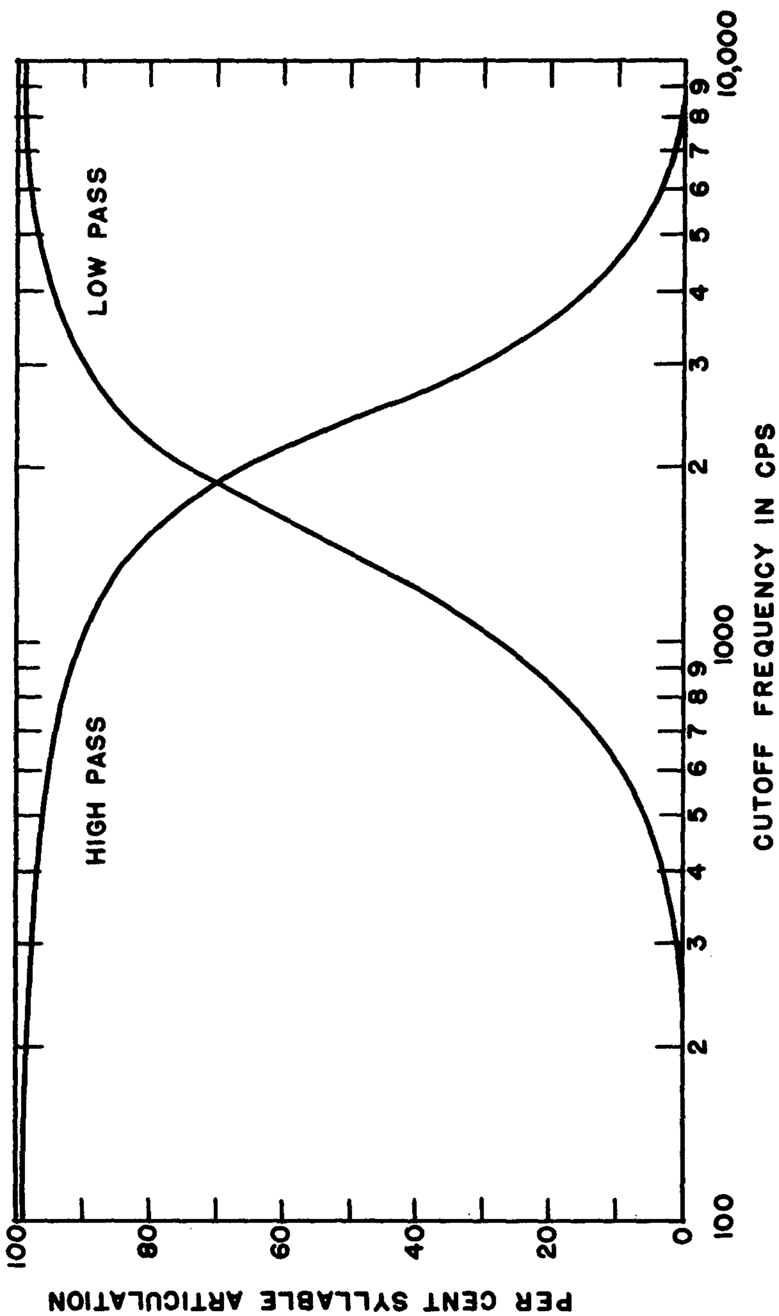
It is to be emphasized that Beranek's chart is applicable only to cases in which the amount of distortion of the speech along the frequency dimension does not change abruptly and in which the spectrum of the masking noise is reasonably uniform. For example, the chart can certainly not be used to predict the intelligibility of speech masked by a pure or complex tone. To a first approximation we may replace a single-frequency masker (that is well separated from other components of the masking signal) by a band of noise having the same sound pressure level and whose bandwidth is equal to the critical band. A more general but also more complex procedure for the computation of articulation index has been presented by Fletcher and Galt 125/. This procedure presumably applies to all types of distortion and to different masking spectra.

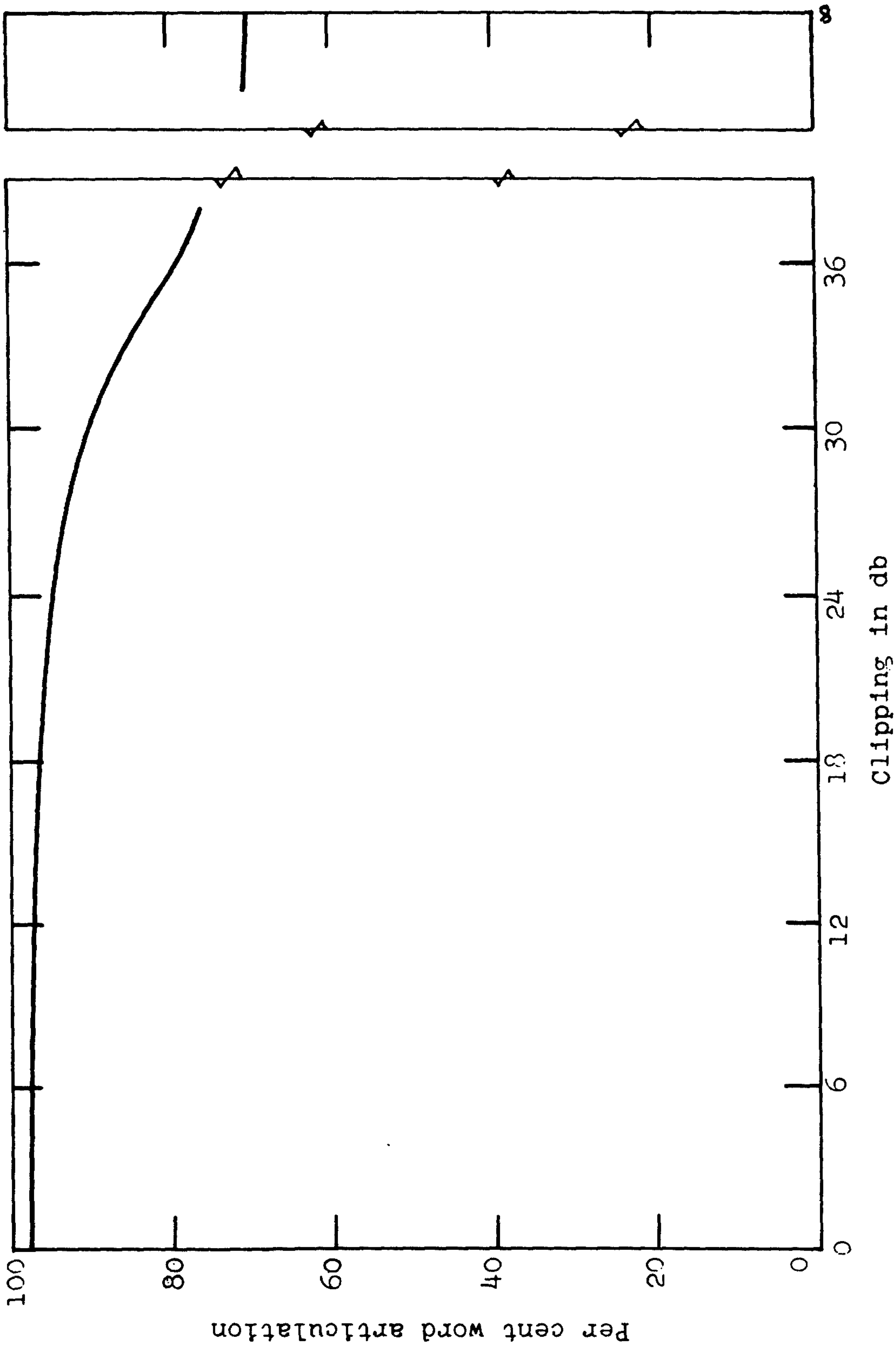
Speech Interference Level. The computation of the articulation index is frequently rather time-consuming, and such detailed calculations are often not warranted in engineering practice. Also, measurements of the spectrum of the masking noise are not made in sufficient detail to define at each frequency the spectrum level of the noise. Usually the sound pressure level is measured in octave bands of frequency, four of which are shown by the vertical lines in Fig. 16.39.

About 80 percent of the important range of speech frequencies is covered by the three octave bands 600-1200, 1200-2400 and 2400-4800 cps. This is shown in Fig. 16.38 in which the frequency scale is distorted in such a fashion that equal distances along the scale correspond to equal contributions to articulation index. Specification of the levels of continuous spectrum masking noise in these three octaves provides data that permit computation of the articulation index to a reasonable degree of approximation 126/.

Figure 16.35

Syllable articulation for speech passed through high pass and low pass filters in the quiet. The gain is adjusted to a value that gives maximum articulation score (From French and Steinberg 105/).


LOW PASS
HIGH PASS
PER CENT SYLLABLE ARTICULATION
CUTOFF FREQUENCY IN CPS
100
80
60
40
20
0
100
2
3
4
5
6
7
8
9
1000
2
3
4
5
6
7
8
9
10,000



Per cent word articulation
Clipping in db
100
80
60
40
20
0
0
6
12
18
24
30
36
∞

The speech interference level has been defined as the arithmetic average of the sound pressure levels (in decibels) in the three octave bands 600-1200, 1200-2400 and 2400-4800 cps. It is a single number that indicates the interfering effect of noise on speech.

A masking noise following the contour of the level of the speech minima in Fig. 16.38 would have a speech interference level of about 43 decibels. For a speech level of 69 db at one meter, which corresponds to a raised voice, a masking noise with a speech interference level of 43 db would have a negligible effect on intelligibility. As will be shown in Section 18.3 reliable conversation can be carried on at a much higher speech interference level.

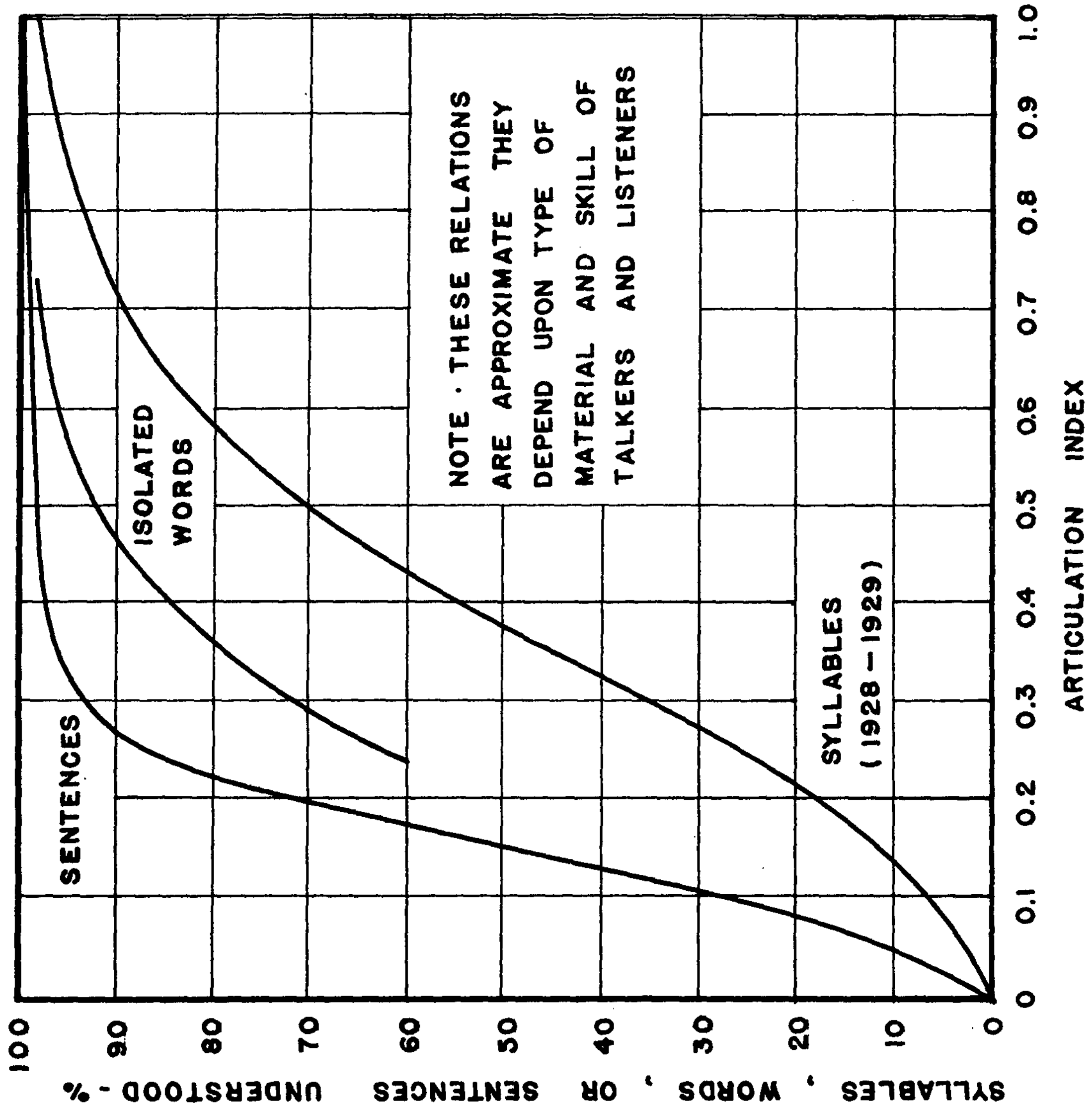
A more detailed discussion of the speech interference level, its applications and its limitations are presented in Section 18.3, which deals with speech communication criteria for noise control.

Figure 16.36

The effects of peak clipping upon the intelligibility of monosyllabic words. When peak clipping is infinite, the articulation score is approximately 70 percent. (After Licklider and Miller 123/).

Figure 16.37

Approximate relations between articulation index and articulation score for several types of test material. (From French and Steinberg 105/).


SYLLABLES , WORDS , OR SENTENCES UNDERSTOOD - %
ARTICULATION INDEX
SENTENCES
ISOLATED WORDS
SYLLABLES (1928 – 1929)
NOTE · THESE RELATIONS ARE APPROXIMATE THEY DEPEND UPON TYPE OF MATERIAL AND SKILL OF TALKERS AND LISTENERS
0
10
20
30
40
50
60
70
80
90
100
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

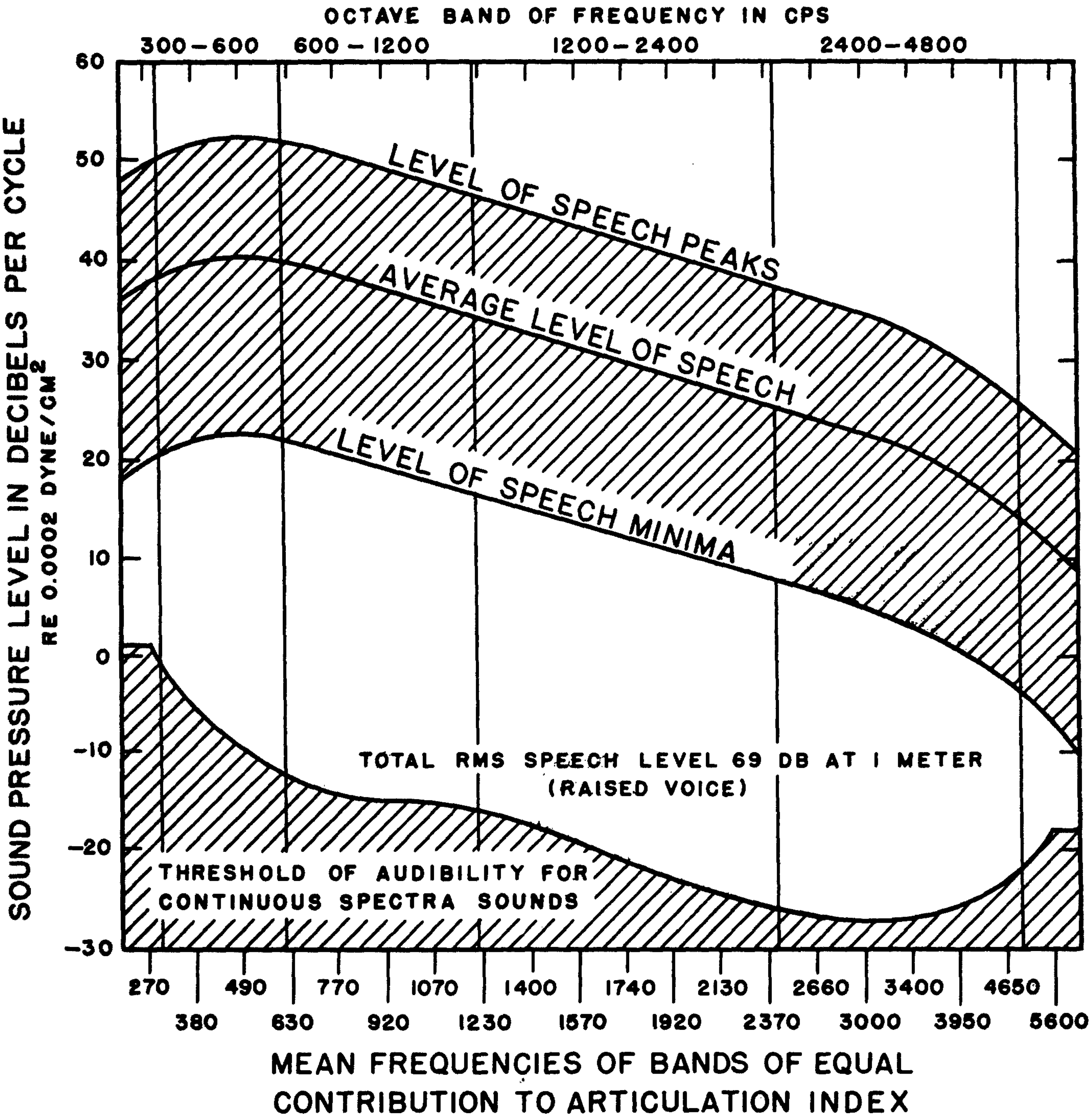

OCTAVE BAND OF FREQUENCY IN CPS
300-600
600-1200
1200-2400
2400-4800
SOUND PRESSURE LEVEL IN DECIBELS PER CYCLE
RE 0.0002 DYNE/CM²
60
50
40
30
20
10
0
-10
-20
-30
LEVEL OF SPEECH PEAKS
AVERAGE LEVEL OF SPEECH
LEVEL OF SPEECH MINIMA
TOTAL RMS SPEECH LEVEL 69 DB AT 1 METER
(RAISED VOICE)
THRESHOLD OF AUDIBILITY FOR
CONTINUOUS SPECTRA SOUNDS
270
490
770
1070
1400
1740
2130
2660
3400
4650
380
630
920
1230
1570
1920
2370
3000
3950
5600
MEAN FREQUENCIES OF BANDS OF EQUAL
CONTRIBUTION TO ARTICULATION INDEX

Figure 16.38

Chart for computing the articulation index for speech subjected to frequency distortion and masked by continuous spectrum noise. If the level of the speech differs from the level shown on the chart (69 db), the band representing the speech area is moved up or down accordingly, The shape of the spectrum is likewise distorted to account for any frequency distortion in the communication system. The spectrum level of the masking noise is plotted on the graph. The fraction of the total speech area that projects above the masking noise is equal to the articulation index (From Beranek 106/).

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CHAPTER 17

EFFECTS OF NOISE ON HUMAN BEHAVIOR

17.1 Introduction

"Does noise affect human behavior?" Almost universally, this trivial question will be answered by a firm "yes". Suppose, however, we probe deeper and ask two more specific questions: "How does noise affect human behavior?" and "What noise affects which behavior?" There is less agreement on the answers to these two questions, and in many cases no definite answers have been proposed.

Opinions expressed in the literature are divided roughly into two camps. (See Kryter 1,2/, for example). Certain authors try to show that noise, like the weather, controls practically all of man's activities, and that it influences his efficiency and his creativity. Some even proclaim that noise is a determining factor in man's physical and psychological well-being, to a point where noise is blamed for the declining birth rate and for the increase in the number of admissions to mental hospitals 3,4,5/.

On the other hand there is a group that is smaller in size but not less firmly rooted in its convictions. These authors admit that noise interferes with auditory communication, and that it may even - through the fact that in many activities people have to talk to each other or would like to be able to talk to each other - interfere with certain communication-dependent human functions. Concerning most other claims, however, this group points to the negative results of controlled laboratory experiments. Most of the laboratory data collected to this day indicate that many of man's activities are relatively unaffected by noise.

Before attempting to review at least part of the evidence upon which the two opposite camps base their arguments, we should see if we can agree on what we are arguing about. What do we mean when we talk about "noise" and about "behavior"? Suppose we ask a communication engineer whether a particular communication link is able to transmit signals in the presence of noise. In return, the communication engineer would want to know what signals are to be transmitted and what kind of noise is present. Our problem is somewhat analogous. In order

to predict the effects of noise upon human behavior, we must specify both the noise and the behavior (i.e., the "signal"). The accuracy of our predictions will depend upon the precision of our measurements of both the noise and the behavior.

Various definitions could be given for the two terms 6/. The Acoustical Terminology of the American Standards Association defines noise as "any undesired sound". Thus our instruments must measure the characteristics of an acoustic event that people have designated as undesirable, or an acoustic event that we have good reason to assume produces deleterious effects.

The human behavior in which we are interested expresses itself by all kinds of physiological and psychological responses. Preferably the responses should be sufficiently obvious that they can be observed by others, but we cannot usually be too restrictive in the way in which we measure behavior. We shall accept data from opinion polls, complaints to newspapers, management or even neighbors as expressions of behavior, provided they can be observed with adequate reliability.

In the following sections we shall review some of the reported evidence that relates noise and behavior. We shall not repeat here the data on masking (Sec. 16.2 and 16.4), in which noise (which in some cases could even be a pure tone or a piece of popular music) interferes with the detection of acoustic signals. Since masking studies are usually integrated with the basic data on hearing, we discussed them in Chapter 16.

We do not claim to have treated the subject of masking exhaustively. For example we have not studied cases of masking that involve high-intensity, low-frequency sounds. Furthermore, we have not dealt with such problems as the possible interaction of vibratory phenomena with the detection of acoustic signals. In both instances, lack of adequate data explains our reluctance to speculate.

Our treatment in this chapter will not attempt to review the literature in detail, since the literature is too massive and also too complex for such a task. We shall, however, attempt to indicate the considerations that are important for a critical understanding of the work that has been reported, and we shall also try to point out the problems that exist in the various areas.

17.2 Effects upon Bodily Functions Other than Hearing

The effects to be considered here fall into two general categories: (a) intersensory effects, i.e., situations in which the presence of a noise stimulus affects psychophysical responses to other sensory stimuli, and (b) effects of noise upon general bodily functions such as heart rate, metabolism, or galvanic skin response.

Intersensory effects at normal levels of stimulation have been of considerable interest to psychologists for many years. Apparently there are no really safe generalizations from present data. Hence we shall not attempt to discuss whether an acoustic stimulus enhances or inhibits detection of, say, a visual signal. Our chief concern in this handbook is with those intersensory effects that are observable in noise of high intensity.

It is relatively easy to see how general bodily functions might be affected by the presence of an acoustic signal if such a signal connotes danger (sound of approaching bomber or missile) or if it is associated with a pleasurable event. It is also clear that a person who suffers from insomnia may develop various kinds of symptoms if the sound of an approaching airplane or truck intrudes just when he is about to doze off. More dramatically, a person may be frightened by an unexpected noise just as he might be startled if he were suddenly drenched with ice-cold water. It is clear that we cannot pretend to establish acoustic design criteria that takes into account the unexpectedness or the connotation of such noises. Here again we must restrict our survey to those changes in bodily responses that can be observed reliably (though not without variability between individuals). This again amounts to a restriction of our interest to the effects of high-intensity noise.

For the purposes of this section, we shall refer to noises in and above the zone of tolerance thresholds as high-intensity noises. The overall sound pressure level is approximately 120 db and above.

We should remember that in environments where the SPL is so high, man often finds himself in the presence of many other kinds of stimuli that may be emitted by high-energy sources (for example, the heat and fumes given off by a jet engine). Man may often, especially in military situations, find himself in a position of considerable stress in which noise is only one of several stressful stimuli. In such circumstances it

would be inadvisable to attribute changes in man's bodily performance to the noise alone if careful control of the other variables is not guaranteed.

With the development of jet aviation, considerable attention has been focused on the effects of ultrasonics. Following World War II, many wild reports attributed extraordinary powers to sound waves at inaudible frequencies. Today there is agreement that most of the effects that have been reliably observed 7/ were a function of the energy in the acoustic stimulus and not of the frequency.

The remarks on the effects of ultrasonics should be tempered by the realization that the short wavelengths permit focusing of the energy in the ultrasonic beam to an extent that is clearly impossible in the audio range. Parrack 8/ has pointed out, incidentally, that turbo-jet engines produce relatively little energy in the ultrasonic range.

Some of the above observations are contradicted by the findings of Grognot 9/. Describing certain changes in the blood circulation of his subjects after exposure to airborne sounds of frequency 25 kcps, Grognot states that the effects were lacking for subjects who were deaf or who wore ear protectors. Confirmation by other experiments will be needed before these observations are generally accepted.

Recently certain European authors have reported effects on the hearing of small animals after exposing the animals' ears to large doses of ultrasonics. There is, however, little reason to conclude that ultrasonics have a particular effect upon the auditory system. Since ultrasonics interact in general with biological materials, there is no reason why they should not also affect animals' ears.

In a paper entitled "Physiological and Psychological Effects of Noise," Parrack 10/ summarizes the findings of the Aero Medical Laboratory at Wright-Patterson Air Force Base in the following manner:

"Action of Sound on Other* Body Mechanisms

"Receptors in the Body Surface: Low frequency sound waves stimulate receptors in the skin. A sound at a level of

* i.e., other than the mechanism of hearing

110 db can be felt by the hand when the frequency is around 100 cps. Under certain conditions these sensations from body receptors can be sufficiently strong to give the impression that the earth or the building that supports us is vibrating violently.

"Receptors of the Joints and Tendons: Low frequency sound waves may vibrate the muscles of our arms or legs and also the thoracic and abdominal walls. Receptors located in joints or in tendons are stimulated. This may lead to reduced ability to perform critical manual acts. Sensations from these receptors acting in combination with those from the body surface receptors cause us to rate the sound field as very unpleasant or extremely annoying.

"Heat Receptors: In very intense sounds (ca 150 db) at frequencies between 2000 and 25,000 cps there may be a mild warming of the body surface. If there are narrow channels between areas of skin, as when the hand is held in the sound field with the fingers loosely approximated, the heating action may be sufficiently great to cause actual pain. Heating is also pronounced under the edge of one's collar or at the cuffs of a coat or shirt. Certain items of clothing may absorb sufficient sound energy to become quite warm (a temperature rise from 32°C to 59°C in 1 min.) and thus secondarily stimulate receptors in the skin. Sound fields of such intensities are rated very unpleasant and are obviously avoided when possible.

"Absorption of Sound at the Body Surface: Since the publication of the data relating to the action of high frequency sound waves on small furred animals 11,12,13/ there has been much speculation about the action of intense high frequency sound on man. Frings, Allen and Rudnick, 12/ exposed mice to sound waves from a siren at levels of approximately 160 db. They pointed out that the animals were killed by overheating and that the heating process proceeded much more rapidly in furred animals than in those from which the fur had been removed. At the Aero Medical Laboratory these studies have been confirmed 14/ using rats as the experimental animal. At the same time it was observed that men exposed to the same sound fields were not injured but occasionally experienced heating between the fingers as discussed earlier under heat receptors. Investigation of the absorption coefficients of the body surfaces of animals and man 14,15/ provided an adequate explanation of the difference in the action of the sound energy. I shall simply summarize the present status, here, by saying

that there is no evidence that air-borne sound waves at ultasonic frequencies constitute a hazard to man. There is definite evidence that ultrasonic frequencies at the energy levels generated by current aircraft power plants do not constitute a hazard to man. On the other hand the physical properties of the human body are such and the energy level of the sound waves, at frequencies below 200 cps, is such that there is a probability of injury from the low frequencies. The major hazard to man of sound in the frequency range 200 cps to 20,000 cps is the action on the human ear and possibly on other specialized receptor systems when the sound waves are extremely intense." 7,16/

Elsewhere, Parrack 17/ has given these further details on vibratory phenomena:

"Sound levels of 130 db and above stimulate receptors in the mouth, nasal passages and external ear canal. The end organs stimulated are probably the skin pressure receptors.

"When the sound level at certain frequencies is about 140 db we perceive a strong sensation of vibration of the skull. This sensation is most prominent when the frequency is between 750 and 2000 cps. The frequency arousing maximum sensation at a given sound level may be different for different individuals. These sensations are particularly annoying and few persons willingly remain in such a sound field.

"In the presence of sounds at levels above 140 db, especially when the frequency is below 1000 cps, the chest wall, the abdominal wall and even the arm and leg muscles are set in vibration. These vibratory sensations become more prominent as the frequency decreases at least down to 100 cps. Such sensations are not only annoying but at least in some individuals nausea and vomiting are induced. There is also evidence that the vibrations of the body muscles produce reflex inhibitions which make precise muscular control difficult. These reactions markedly reduce man's performance efficiency."

In a Memorandum Report in May, 1948, Parrack and his collaborators 18/ state also:

"There have been occasions, during exposure to these low frequency sound fields, both in the laboratory and at the jet engine test cells, when personnel have observed a "weakness in the knees" or an apparent general weakening of the body supporting musculature. This sensation is not accompanied

by faintness or vertigo and is probably not the result of a true muscular weakness. It would appear to result from an effect on the proprioceptive reflex mechanism since with conscious effort one can maintain the normal erect position usually maintained by reflex mechanisms."

Finally Parrack and others report blurred vision in the presence of intense vibration of the cranial bones or of the eyeballs. Recovery after moderate exposure is apparently immediate and complete as soon as the subject leaves the sound field.

More recently, Dickson and Chadwick have reported their "Observations on Disturbances of Equilibrium and Other Symptoms Induced by Jet-Engine Noise." 19/ They refer to mild and transitory symptoms of momentary dizziness, unsteadiness and even "mental aberration" in personnel working close to turbo-jet engines. They suggest that the observed phenomena are a manifestation of the "Tullio reaction," i.e., the production of head motion by means of loud sounds. (See, for example, Fig. 48 of ref. 20/). Dickson and Chadwick feel that the above-mentioned symptoms may be due to intense acoustic stimulation of the vestibule or even to a leakage phenomenon between the auditory and vestibular branches of the eighth nerve. The British authors state that the symptoms appear to be more marked if engine speeds are changed than when an engine is run at constant speed.

Besides the effects we have designated as intersensory, there are numerous studies dealing with the effects of noise upon various physiological functions. Kryter 1/ has made a careful review of the literature in this area. He finds that for steady noise of SPL below 120 db, human organisms seem to adapt in a satisfactory manner, provided they are given enough time to do so. One of the latest studies that confirm these conclusions is that by Finkle and Poppen 21/. We quote the following paragraphs from the summary of their paper:

"Experimental data derived from exposing 9 volunteer Navy enlisted men and a medical officer at various positions near a General Electric I-16 turbo-jet engine for a total of 20 hours over a period of 6 weeks revealed the following: a) Increase in fatigue and irritability during the entire course of the experiment in 7 of the 10 subjects. The others noted no change. b) Early, temporary, sharp decrease in auditory acuity in the 'conversational frequency range' of 512 to 4096 cps. Normal hearing was gradually regained by the 7

subjects affected within 12 hours or less after onset. c) Loss in weight of 5 1/2 to 19 pounds in 5 of 9 subjects. It is questionable that this finding is a result of the experiment. d) Rise in fasting blood sugar during a one-hour period of exposure to the jet engine in all subjects and decrease in the fasting blood sugar level after a two-hour exposure in 7 of the 10 test subjects. e) Normal findings, unchanged from pre-experimental values, were noted for blood counts, urinalyses, kidney function tests, bleeding and clotting times, icteric indices, upper gastrointestinal x-ray studies, electrocardiograms and electroencephalograms during and after the experiment.

"Noise analyses of this engine revealed overall intensities of 120 db to 7500 cps, and peaks of sound were noted up to 38,000 cps."

There are, of course, practical situations for which the Finkle-Poppen experiments would not constitute sufficiently realistic tests. We can think of instances in which an individual would not have time to adapt to noise, but in which the important instant is at the onset of the noise. An understanding of such noise-emergency situations is clearly not possible at present.

Hale 21/ recently reported that increased adreno-cortical activity was associated with intense engine noise. It is certainly not unreasonable to assume that there are levels of acoustic noise that will overtax the adaptive and compensatory mechanisms of man.

Some individuals may have to carry out taxing tasks in surroundings where noise levels are of the order of 150 to 160 db. The first necessity is to provide all the ear protection that is available. But we may have to go further. We may have to set up tests that will select men who, on the basis of their physiological responses, their motor skills and other aptitudes, are best qualified to live and operate in such sound fields.

17.3 Noise and Annoyance; Noise and Performance

From time immemorial men have complained about noise. Poets and housewives have been equally eloquent in their tirades, declaring that noise "drives them crazy". While we have no reason to doubt the sincerity of such complaints, they do not have the status of scientific evidence.

People complain about many noises because they "annoy" them, or because they think the noise interferes with the performance of their work. These complaints occur though there are usually no direct effects on body functions other than hearing (the subject of Sec. 17.2), and there is no question of permanent or temporary effects on hearing because of exposure to high intensities (Sec. 17.4). We shall be concerned in this section with the general question of the relation of noise (not necessarily high intensity noise) to annoyance and to the performance of tasks.

Noise, a Source of Annoyance. Annoyance is not a concept that we can easily quantify. It is complex, as some trivial illustrations will indicate. For example, most people in noisy cities have learned to sleep in this environment, although some of them may have trouble falling asleep in the country, with its relatively low-level noise of rustling leaves, frogs and birds. Apparently, man can become adapted to a large range of physical environments, although all people do not adapt equally well. We see that the important physical quantity is not simply overall sound pressure level, or even the octave band pressure levels. Except at extremely high levels, people's reaction to noise depends upon many factors, only a few of which are the acoustic characteristics of the noise.

For a given noise, we can certainly state that annoyance will increase with intensity (and hence with loudness), but we are unable to measure a general threshold of annoyance. Such a judgment would depend upon the task that the noise interferes with, the kinds of noises the subject has been exposed to in the past, etc. We could, for example, rank various sources of sound in the order in which they would annoy us if we were listening to a concert. The same rank order would not necessarily apply if the noise interfered with our sleep.

It is apparent, then, that annoyance responses to noise are truly multi-dimensional. They are compounded of reactions to noisy events that irritate you, that startle you, that prevent sleep, that prevent you from calling to your child, that

make it impossible for you to hear the radio, that strike you as most unnecessary, etc.

Recently, the French acoustician Moles 23/ has tried to classify noises into three categories: (1) those that are disagreeable or "get on your nerves"; their level is less than 40 db, and they are effectively suppressed (according to Moles) by masking; (2) the noises that bother, disturb or annoy you, whose levels are between 50 and 80 db; their symptoms are interference with speech communication, nervous fatiuge and interference with abstract thinking; and (3) the destructive noises that lie above 100 db, and that attack directly the biological organism. If some of the above terms were defined by operations of measurement, and if certain further specifications of the noise were provided beside the overall level, a classification such as Moles' can, perhaps, provide hypotheses for experimental investigations. For the present, however, the classification is merely a verbal scheme with little power of prediction.

Let us now turn to laboratory investigations of the concept of annoyance. It stands to reason that we should proceed with caution in extrapolating from laboratory findings in this area to the everyday behavior of our fellow citizens. Kryter 1/ reviews most of the experimentation and comes up with certain generalizations on various aspects of noise such as its unexpectedness, inappropriateness and intermittency. The acoustical characteristics that he considers are the intensity and the frequency pattern of the noise.

Reese and Kryter 24/ conducted an experiment in which their subjects were asked to equate bands of noise for loudness and for annoyance. For the latter task the five subjects adjusted the intensity of bands of noise (250 mels wide) until they felt that they were each equally tolerable when compared to a standard band. The noises were presented by means of earphones. The data of Reese and Kryter (with their considerable inter-subject variability) show that at the higher frequencies above 3000 cps equal annoyance can be achieved with less intensity than equal loudness. For speculations on the physiological basis of this phenomenon, see Husson 25/.

Pollack 26/ in a later experiment required three subjects to discriminate various psychological attributes of bands of noise. Annoyance (defined as "the disturbingness of bothersomeness of the sound) turned out to be one of the attributes that was relatively clearly differentiated from loudness. At

both ends of the frequency spectrum Pollack's observers assured him that bands of noise less loud than the standard band (either 60-5000 cps or 1290-1900 cps were equal to it in annoyance.

G. A. Miller in an investigation on the masking of speech 27/, was also concerned with the problem of annoyance. Since his approach coincides with much that we have already said, we shall quote a rather extensive passage from his paper:

"When we take this problem [of annoyance] into the laboratory, it seems to disappear right in front of our ears. The major difficulty rests in the fact that the listener's attitude is so important. If he is engaged in difficult mental work, it may be relatively easy to annoy him. But if he listens with a defiant attitude, any attempts to upset him with strange noises may prove more amusing than effective. And since most of the sounds we can use in the laboratory are out of context and relatively meaningless, the task of being successfully obnoxious is practically impossible. Annoyance depends primarily upon the particular listener and the particular situation in which he finds himself.

"If, however, we are content to ignore some of the situational variables involved, it is possible to ask listeners to compare different sounds on the basis of their "annoyance value." Some simple listening situation is standardized and the listeners compare pairs, use a rating scale, or rank-order an array of sounds. One can then evaluate the variables contributing to annoyance value as defined by the situation, although the safety with which the results can be extended to other situations is open to question.

"Listeners were presented with pairs of sounds and were instructed to indicate which of the two sounds was more annoying. In making this decision, the listeners were told to judge which sound of the pair would be more unendurable if they had to listen to it for a long period of time. These instructions, therefore, constitute the definition of annoyance. Fairly consistent results were obtained with groups of 10 to 20 listeners, and the scale of annoyance constructed in this way agreed closely with results obtained with rating or rank-ordering procedures.

"As an illustration, the results obtained with stepped patterns of tones will be considered. Eight different variables in the tonal pattern were studied for their effect upon annoyance-value.

"1. The higher the pitch of the component tones, the greater the annoyance-value. The range of frequencies tested was from 200 to 1500 cylces.

"2. A wide range of frequencies between the highest and lowest steps is more annoying than a restricted range. Listeners reported that the wide range of component frequencies tended to be perceived alternately, first as a complete pattern and then as two patterns, one of high and one of low pitch. This effect is very similar to figure-ground reversals in visual perception.

"3. The addition of continuous tones to the stepped pattern of tones produces complex effects dependent upon the frequency-relation between the tones. Beats give the sound a rough pulsing irregularity which the listeners disliked.

"4. Listeners asked to compare continuous sounds of different wave-shapes found the complex sounds, especially brief pulses, more annoying. In general, the sine wave was found to produce little annoyance.

"5. Patterns of 3, 4, 6 and 12 tones were compared, but the number of different steps in the complete pattern had little effect on the judgments of annoyance.

"6. If one of the steps of a pattern is slightly longer in duration than the others, a rhythmic quality is added which the listeners judged to be more annoying than tones of equal duration. Even more annoying, however, is the pattern in which all the tonal durations are randomly varying.

"7. A slow rate of repetition for a pattern of tones is considered slightly more annoying than a rapid rate.

"8. Up to a certain limit, the annoyance-value is increased if silent intervals are introduced between the successive steps.

"These results typify listeners' responses to meaningless sounds. When meaningful sounds like speech or music were used, the listeners refused to apply the word "annoyance" in describing them. Annoyance did not seem to be a proper dimension of such sounds, but the listeners were agreeable to calling the sounds "distracting." Apparently, meaningful sounds have a higher "attention-value" than meaningless sounds.

"These experimental results, supplemented by results obtained with other types of sound, indicate that annoyance is related to three aspects of the sound.

"Loudness. The most important single factor in determining annoyance-judgments is the intensity of the sound. With sufficient intensity, any sound can be made annoying, and extremely loud sounds produce actual pain. Since this variable is so fundamental to annoyance, care was taken to equate the intensity of the signals when other aspects were being studied.

"Pitch. In general, sounds having their energy concentrated among the higher audible frequencies are more annoying than low-frequency noises. In this respect, the frequency of the sound alters its annoyance-value in a manner opposed to the effect on masking. With a low-frequency noise we cannot hear speech, but with a high-frequency noise we are more apt to be annoyed.

"Modulation of Loudness and Pitch. A third important factor is the modulation which the sound undergoes. Listeners report that they prefer to listen to continuous, unchanging sounds, and that a sound changing irregularly from moment to moment is more annoying than a sound which is changing regularly. Listeners feel that the distraction of a changing sound is less desirable than the boredom of a constant sound, and they retain this opinion even after many hours of articulation testing in the presence of different noises. Apparently the changes in loudness are more effective than changes in pitch, but the individual differences on this point are too conspicuous to permit a safe generalization.

"Judgments of the pleasantness, indifference, and unpleasantness would probably have led to very similar conclusions. Thus, while the results may be interesting as an exercise in experimental esthetics, the character of the problem has somehow been altered by the experimental approach. The principal concern, it will be recalled, is with annoyance as a hazard to vocal communication. On this score the results are consistently negative, and at no point in the experimental results is there unequivocal evidence that the articulation scores obtained by trained listeners in the presence of an annoying sound were lower than the scores obtained in the presence of an indifferent sound which had the same acoustic spectrum. With the attitude adopted by listeners in the laboratory situation, annoyance is not a hazard to communication. And yet, sounds do differ in annoyance value, and annoyance or

distraction does sometimes interrupt our verbal flow. Perhaps the most reasonable generalization, therefore, is that when a listener find himself in a situation where he is vulnerable to auditory annoyance, he is most vulnerable to loud, high-pitched, unpredictable sounds. Just what situational and attitudinal factors contribute to his vulnerability,however, this research does not reveal."

It is safe to predict that people will continue to investigate the problem of annoyance by noise. Let us hope that they will be able to find at least a partial answer to the problem by adopting a reasonably operational definition of the annoyance concept in their experiment or opinion poll.

Noise, an Enemy of Performance? Noise has often been blamed for poor performance, for lack of efficiency, labor turnover and absenteeism. Many industrial field studies actually make such claims. Kryter's 1/ analysis has shown the extent to which most of these studies neglected to control variables that could have been responsible for the effects that were observed. Among the most important factors besides environmental variables such as heating, lighting, ventilation, etc. that may have been overlooked are (a) the role of speech communication in the working process, and (b) the fact that a field investigation that shows concern of the management with labor conditions may result in improved performance on the basis of motivational factors alone.

A physician who wants to test the effectiveness of a new drug divides his population into two groups. He may decide to administer his drug to one-half of the population, while giving sugar pills to the other half. Such a procedure presumably equalizes the psychological situation of both groups, since they have both been given equal consideration. Likewise, one might want to use in an experiment good ear protectors for one group and ineffective ones for the other in order to duplicate this medical technique.

Recent laboratory studies demonstrate little, if any, lasting effect of noise upon performance. This sharp contrast between field studies and laboratory studies is not too surprising if we remind ourselves that the listener's response is not just a function of the acoustic stimulus, but depends upon other factors.

As an example, we should like to refer to a routine performance under noise by Mech 28/. The author gave four

groups of fifteen subjects verbal addition tasks for thirty minutes each day: fifteen minutes in the "quiet", and fifteen minutes in an environment of "verbal noise" (a record from the series "I Can Hear It Now" was played at an average level of 70 db SPL at the subjects' position). All subjects (undergraduates) were told to add as rapidly and as accurately as possible; they were told that they would be given credit for the total number of correct responses. The various groups were instructed as follows: Group A was told that the experiment concerned the effects of noise on work. Group B was told the same story and also shown (faked) graphs indicating that in previous experiments people had performed better in the presence of noise. Group C was told the same story as A, except that they were shown (faked) graphs indicating that people had previously performed better in the quiet. Finally, Group D was treated like Group C, except that their (faked) graphs showed that while in a previous experiment people performed at first better in the quiet, they finally performed better in noisy conditions. The results were striking. There was no significant difference for Group A between performance in noisy or quiet conditions, Groups B, C and D behaved (at a statistically significant level) just as the (faked) graphs had "instructed" them to. We have no opportunity here to go into details of the results, but we feel that all future investigations of the effect of noise on performance should study them carefully.

Perhaps one of the most comprehensive studies of the effects of noise on psychomotor efficiency was conducted at the Psycho-Acoustics Laboratory of Harvard University during World War II. (See references 29, 30 for a detailed description of the experiments). Five carefully selected subjects participated in the tests during a period of two months. The various tests were administered under two conditions: (a) airplane noise whose overall level was 115 db and (b) airplane noise whose overall level was 90 db (an intensity just sufficient to mask casual laboratory noises and to discourage conversation among the subjects.

"The battery of psychomotor, physiological and psychological tests included measurements of the near point of vision, speed of accommodation, speed of eye movement, visual acuity, muscular tension, heart rate, finger tremor, blood pressure, marksmanship, card sorting, span of apprehension, paper form board tests, steadiness tests, tapping board and standard pursuit rotors for testing motor coordination, coordinated

serial pursuit meters which partially simulated the requirements of instrument flying, tests of coordinated serial reaction time, audiometric measurements of hearing loss, vibration tests, tests of serial disjunctive reaction time, coding tests, judgments of distance, etc."

Noise produced a definite effect on hearing by causing temporary threshold shifts. However, the remainder of the tests showed either indeterminate results (large inter- or intra-observer variability) or showed that the subjects performed as well in the "noise" (115 db) as in the "quiet" (90 db).

In conclusion, the authors of the study state that "airplane noise has at worst only a slightly detrimental effect upon functions involving motor coordination, reaction-time, sensory perceptions, and certain mental functions. In most instances it can be positively demonstrated that noise has no effect, even after exposures lasting seven hours. Functions such as breathing, metabolism, and muscle tension are sometimes affected by noise, but what the effect will be seems to depend upon the kind of individual tested, and simple generalizations are not possible.

"Nevertheless, all subjects seem to prefer not to work in an intense noise, and after a day under acoustic stress, they tend to report a subjective feeling of being more tired and irritable. They have a ringing in the ears and a temporary hearing loss to testify to the severity of the conditions under which they and the pilots of aircraft labor.

"The most severe effects of noise are upon the ear itself. Speech communications are impaired and temporary losses in hearing are produced".

This study has been much quoted and also at times criticized. It would seem unwise to extrapolate too far from the performance of five carefully selected laboratory subjects under two conditions of noise to what might happen to a group of unselected subjects in 30 db more noise in a real life situation. Studies such as these, and those conducted by Hanley and Williamson 31/ and Smith 32/ raise important methodological problems. Can we expect to bring problems like noise-induced annoyance, or noise-induced decrement in performance into the laboratory without disembodying them at the same time?

A promising step in that direction seems to have been made by Broadbent 33/ in England. He demonstrated, in the laboratory, deterioration in the performance of certain tasks in the presence of intense noise. His ten subjects seemed unaffected by the presence of noise if their task was an easy one. When given a more difficult "vigilance-task," their performance on "noise days" was worse than on the quiet days that came before or after. This is perhaps one of the ways of bringing field and laboratory data together: Make the laboratory situations more like real life and let us bring the field situations under better control for variables other than noise.

17.4 The After-Effects of Exposure to Sound Upon Man's Hearing

A study of these effects is obviously of crucial interest if we wish to understand the effects of noise upon human behavior. We have seen that sounds may affect man in spheres other than the auditory one. It is in the realm of hearing, however, that the most striking and perhaps also best understood effects take place.

In earlier sections we have dealt with the interference of simultaneous noise with such auditory functions as speech communication. We have seen that masking can be described as a temporary change in man's sensitivity to acoustic stimuli. We have shown that masking involves not only a shift in threshold but also modification of such psychological functions as loudness, pitch, localization, etc. When we examined the subject of masking our attention was focused upon the interference effects of the noise while it was on. We did not ask ourselves at that time what happens after the unwanted sound ceases impinging upon our eardrums. What happens in the wake of any acoustic stimulus?

The answer to this question is, as usual, not a simple one. It turns out that we need to specify a considerable number of parameters before we can expect to give a set of adequate answers. There is, however, a physiological mechanism that we should examine in some detail before we approach the specific topic under discussion.

Organisms are exposed to all sorts of stimuli, i.e., to all kinds of interactions with their environment. These interactions involve, in general, an energy transfer from the environment to the organism. Much of the time, organisms must "defend" themselves against this continuous bombardment in one

way or another. One of the most effective defenses is the mechanism called adaptation.

We can hardly enter here into a technical discussion of the various kinds of adaptation that exist and of the chemical changes that seem to underlie the phenomenon of adaptation. Suffice it to say that in practically all instances an organism's response to a continued stimulus decreases after the initial response burst.

Adaptation exists apparently at all levels of organization of living organisms. There is adaptation at the level of a single nerve fiber, there are adaptation phenomena in whole populations of nerve fibers, and, finally, there are phenomena designated as adaptation that involve the behavior of the total organism. This semantic confusion should not lead us to assume that these different processes have necessarily the same course or are otherwise quantitatively similar.

Adaptation exists in all of man's sense departments though apparently to different extents. We are all familiar with the fact that people adapt considerably faster to smells and skin pressures than to optical and acoustical stimuli. This state of affairs has important consequences; since the senses of vision and audition relay most of the information that man receives about the world in which he lives.

You will remember that in a masking situation man's sensitivity to acoustic stimuli is reduced while the masker is present. This has been known as the "line-busy" effect. You will also remember that this reduced responsiveness is not identical for various stimuli. It is clear, however, that a cessation of the masker will not bring about an immediate recovery of the organism's normal condition. In contrast to vacuum tube circuits, biological entities do not respond instantaneously, in the sense of microseconds. You may have heard of something that sounded to you like an organism's time constants; you may be familiar with the terms absolute refractory period and relative refractory period. You may even remember that figures of the order of a millisecond are representative of the absolute refractory period of a nerve, i.e., of the period during which no stimulus, regardless of its strength, is presumed to be able to give rise to a response.

You probably know from your own experience that it takes much longer than a millisecond to recover one's normal sensitivity after an intense flash of light or after a strong burst

of sound, provided the conditions of exposure permit recovery! While there are figures in the literature for relative refractory periods, these figures explain at best only a very limited category of after-effects of exposure. We have to accept the uncomfortable fact that after-effects of exposure come in all sizes, that some of the after-effects are reversible while others are not, and, finally, that even all the reversible effects are not necessarily explainable in terms of a single or simple physiological mechanism.

In view of these observations, we should not be surprised that workers in audition have an entire arsenal of more or less confusing terms to describe the after-effects of stimulation. You will find papers on acoustic trauma, on noise-induced deafness, on stimulation, temporary or experimental deafness, on noise-induced hearing loss, on auditory or post-stimulatory fatigue* (sometimes also called short time auditory fatigue), on residual or after-effect masking, on threshold shifts, on auditory adaptation and so on. The authors of these papers are not trying to be contrary or to make things tough for their readers or themselves. They are faced with such a wide range of observable phenomena that they feel it necessary to invent a small dictionary for their description.

The Parameters of Exposure and Recovery. From the above remarks, it should be clear that we need to specify in detail the conditions under which a group of individuals has been exposed to acoustic stimulation, and the conditions under which their hearing will be tested before we can make statistically valid predictions of their response characteristics at any given time after exposure.

How are we going to specify the exposure stimuli? Since studies involving loss of auditory functions have been conducted both in the laboratory and in the field (i.e., in factories, airplanes, submarines, on the rifle range, etc.) It is necessary to specify carefully the way in which the acoustic exposure stimuli have been measured. It is not unreasonable to expect that laboratory experiments, using earphones, will be carried out in the future under such conditions of calibration that

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* Hood uses this term in conjunction with the term "per-stimulatory fatigue" - a type of fatigue that is detected by measurements carried on during application of the stimulus.

sound pressure levels at the eardrum (or equivalent data) will be available. This was by no means always the fact in past studies where sometimes research workers are said to have mistaken decibels of hearing loss read from dials of an audiometer for sound pressure levels. If loudspeakers are used as laboratory sources, the specifications of the actual stimulus becomes somewhat more difficult unless probe-tubes inserted in the ear (or ears) of the subjects are used as continuous monitors.

Care has to be used when so-called free-field values are specified without the necessary precautions having been taken*. It should be clear that such "free-field" data would have to be corrected before they can become really compared with earphone data (see Pollack 35/) and even then there would remain the fact that the subject's head movements might make it difficult to state the exact conditions of exposure unless a running record of SPL's were taken. The situation is very much the same (only much less definite) when one attempts to specify sound pressure levels in field studies. Unless particular precautions are taken or unless one is in the presence of rather unusual conditions in which the sound field is thoroughly homogeneous, one should really only be satisfied with probe-tube data, i.e., sound pressure levels measured at the eardrum.

So-called average data for the sound pressure levels of a factory, for instance, are acceptable when deviations are stated and when some idea is given of the way in which this average was determined. However, this entire discussion of the method of specifying sound pressure levels would prove rather useless unless we examined the response characteristics of the ultimate indicator in our measuring device. There is little problem if our exposure stimulus is either a pure tone or a reasonably well behaved white noise. Our standard sound level meter gives us reasonably good indication as long as the exposure stimuli do not fluctuate too wildly 36/. However, as soon as we deal with noises in which there is an appreciable peak factor (for instance, the noise that is generated by a drop hammer, described in Sec. 7.4) indicating meters are too sluggish and thus in a certain sense "blind". Under these circumstances the best way of measuring the exposure

* For an up-to-date treatment of the way in which such measurements ought to be carried out see Williams and Cox 34/.

stimulus consists in recording the sound pressure wave by means of a carefully calibrated microphone-amplifier-oscilloscope unit*.

We certainly need to know more than overall SPL's if we want to relate man's impaired auditory functions to the exposure characteristics. Just what kind of frequency resolving power our analyzer should have is not entirely certain at present. Somewhere between levels per cps and overall level there should be a usable bandwidth that will yield meaningful correlations with loss of auditory functions. There is no particular reason for assuming that the critical bands used in predicting auditory performance under conditions of masking will be the most useful concept in a computational scheme predicting recovery functions. Most analyzing equipment yields, as we have seen in Volume I, octave-band levels, and some analyzers go down to half or even third octaves.

Let us turn now to the specification of the time characteristics of the exposure stimulus. If the amplitude distributions of the sound do not fluctuate too much, i.e. if the flow of sound energy is relatively steady, specification of the time characteristics presents no problem. However, if the flow of sound energy is irregular, it is not sufficient to specify only the energy the auditory system absorbs. We must also consider how this energy is packaged in time. At present we are not ready to assign definite integrating characteristics to a meter that measures exposure to noise, since we do not have sufficient experimental data on the significance of the time characteristics of the noise. We must realize that, at present, a single number (be it sound pressure level, energy, or the product of sound pressure level and time) is not necessarily going to do the job of specifying exposure.

Next, let us examine the parameters that come into play when we are trying to assess <u>recovery</u> from exposure. Let us

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* In field measurements of impulsive sounds or of sounds of short duration, the equipment required to perform accurate on-the-spot measurements is rather bulky. Frequently it is more convenient to record the sounds, along with suitable calibrating signals, on a tape recorder. The recordings can then be thoroughly analyzed in the laboratory at a later time, and the necessity of transporting the analyzing equipment is thus avoided.

assume our subjects have been exposed to a stimulus whose characteristics are well-defined, and that we are interested in the recovery of their absolute threshold curve. You may be inclined to ask: What else could we possibly be interested in? We could be interested in practically any other measure of auditory performance, and there are quite a few as we have already seen in Chapter 16. Our conclusions might be rather different depending upon the measure of performance against which we calibrate our recovery studies. A recent paper by van Dishoeck 37/ bears out this contention.

Let us consider first the recovery of the absolute threshold after exposures that do not produce irreparable damage. One of the first questions that arises: How far in time are we to follow the recovery? Must we insist upon a post-exposure threshold that comes within 1 or 2 db of the pre-exposure threshold? If we like that much accuracy, we cannot use most of the standard audiometers since their smallest intervals are 5 db steps. Suppose, now, a subject has recovered within the limits that we have set; does such a recovery guarantee that his threshold will not get worse again? Not necessarily, if we take into account the findings obtained by Bronstein 38/, and more recent data from Hirsh and Ward 39/. In other words, we must make certain that the recovery of the threshold, once complete, is not going to be upset again. We could, of course, measure the recovery of the threshold in a different manner. We might take thresholds at fixed time intervals after the end of the exposure. Such a technique has to be used for experiments in which recovery occurs in a rather short time (several seconds or even fractions of a second).

After exposure to a given sound, the recovery of the subjects must be measured by some kind of a test stimulus. So far, we have not touched upon the question of the relation between exposure stimuli and test stimuli. There are almost unlimited possibilities. We can start out by making the exposure stimulus and the test stimulus the same. We could choose, among pure tones, a test stimulus that is anywhere in the audible frequency domain, i.e., it could be either higher or lower than our exposure stimulus. However, we do not necessarily have to test with a pure tone; we might choose instead a band of noise, a click, a tone pip or even speech. There is no reason why we should expect these different procedures to yield identical results. As a matter of fact, there are certain conditions in which thresholds for certain

test stimuli improve for a certain time interval (so-called sensitization) while the same exposure stimulus will at the same instant in time produce a rather serious hearing loss for other test stimuli.

It becomes clear that no single number can describe recovery any more than a single number can describe exposure. Both exposure and recovery are complex multi-dimensional entities. Hence we find it understandable that we cannot give a simple account of what happens as a consequency of exposure to noise.

Thus far we have talked about the effects of exposure upon the absolute threshold only. It should be clear that we could and probably should pick other aspects of man's auditory performance if we want to be able to describe realistically the after-effects of exposure. Let us enumerate just a few of the functions that have been investigated, though in most instances rather spottily.

Some work has been done on the effects of exposure upon loudness*, upon pitch perception and upon localization of sound sources in space. Studies describing the effects of exposure upon the masked threshold (for speech let us say), on just noticeable differences or on temporal auditory resolving power are still lacking. There are, however, a few not too systematic observations on subjective noises (such as tinnitus) and diplacusis as after-effects of exposure.

Having considered in some detail the parameters of exposure and recovery, we must still give an adequate description of the condition of the individual (or the group of individuals) who has been exposed and whose recovery is being tested. For example, we must find out how normal our subjects' audiograms were at the start of the exposure. We should require a complete otologic examination of our subjects and obtain if possible a diagnosis and classification of any permanent hearing losses with which they are afflicted. We should know the age of our subjects since there are some indications that different age groups are not equally sensitive to exposure 40/.

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* The so-called recruitment phenomenon in nerve deafened patients (see definition in Ch. 15; see also Sec. 16.3) has attracted a good deal of attention.

Next, we might want to inquire into our subjects' previous history of exposure and even into their heredity from the point of view of auditory defects. If data exist showing the subjects' previous recovery functions, we should want to know if they were shown to be particularly sensitive, if previous exposures have given rise to cumulative losses, if, in particular, at the beginning of the exposure the subjects' hearing was normal compared to their own standard (for example, some subjects might be affected by a cold). We should also like to know something concerning the effectiveness of the subjects' middle ear muscles, but unfortunately there is no good test available at present that will give us such information.

The Effects of Exposure. The literature on the broad subject of loss of auditory function after exposure to sound is inordinately large (see Ref. 41/). There are literally hundreds of articles dealing with observations made on animals, with reports of clinical cases, with laboratory experiments on man and with sweeping (though mostly not too well controlled) industrial surveys. Furthermore the period after World War II has seen the publication of at least four important monographs in this general area: Ruedi and Furrer 42/, Davis et al 43/, Theilgaard 44/ and Hood 45/. Then there are the series of important articles by Luscher and Zwislocki 46,47,48/, the Munson and Gardner investigation of "loudness patterns", the Causs and Chavasse study 50/, and the series of reports on short duration auditory fatigue by J. D. Harris and his group 51,52,53,54/; all of these papers are related in some sense to the de Mare's monograph 55/ whose pioneering influence has been felt now for almost 15 years.

In view of the space that we have available here, it would be presumptious to review critically the findings of so many experiments and surveys. This is especially true since, according to our present impression, no overall valid generalizations could be expected to derive from such an undertaking. The various studies we mentioned (and others too numerous to mention) have produced a large accumulation of data; unfortunately most of these data are not strictly comparable since they have not been collected under anything like comparable conditions and since only very few of the data overlap. However, these various studies have posed serious problems and it is essentially with some of these problems that we shall be concerned.

Our major concern here is with the type of permanent perceptive or nerve deafness that represents a significant

change in the normal presbycousis pattern. This type of high frequency hearing loss is found in many noisy occupations (including military services) in which humans are exposed to intense noise repeatedly and for considerable periods of time. However, our interest extends beyond the causal factors of permanent partial deafness. We should like to understand its genesis, its relation to temporary threshold shifts, its relation to the intensity level, the spectrum and the time course of exposure - the three most important parameters of exposure.

We should also like a better understanding of the following questions: Are there cumulative effects of exposure even after the threshold has returned to normal? Are there certain age groups that are particularly vulnerable to exposure? What about the sensitivity to noise of people who already have a certain amount of nerve deafness? Finally, we should attempt to gain some insight into the concomitants of variability in individual susceptibility to exposure, if for no other reason than to be able to design so-called predictive tests separating "tough ears" from "tender ears".

It is hardly realistic to tackle even half of the questions that we have raised. Let us get back to a question we posed earlier: What happens in the wake of any acoustic stimulus?

For a partial answer to this question, we go to laboratory studies practically all of which employ pure tones as exposure stimuli and either pure tones or short pure tones (so-called tone pips) as test stimuli for the recovery. At levels of the exposure stimulus that are not too far above the subject's threshold there occurs a threshold shift at the exposure frequency and at neighboring frequencies. This threshold shift persists for a fraction of a second and is reasonably independent of the duration of the exposure. The initial threshold shift is, however, rather closely related to the sensation level of the exposure stimulus (see Fig. 17.1). The spread of frequencies for which a threshold shift occurs is reasonably symmetrical at these low intensities of the exposure stimulus. There is some disagreement as to whether these threshold shifts are equal in magnitude at low and at high frequencies. Most of the argument revolves around the way in which the exposure stimuli ought to be described: Should we compare recovery of the threshold for equal SPL's, equal sensation levels or equal loudness levels?

As we increase the intensity of the exposure stimulus, the recovery process lengthens. This lengthening is apparently accompanied by two features: (a) recovery at low frequencies seems to occur quicker than at the higher frequencies; (b) the threshold shift now becomes somewhat less symmetrical. In this respect the pattern follows masking contours for strong stimuli with spread of the effect on the high frequency side.

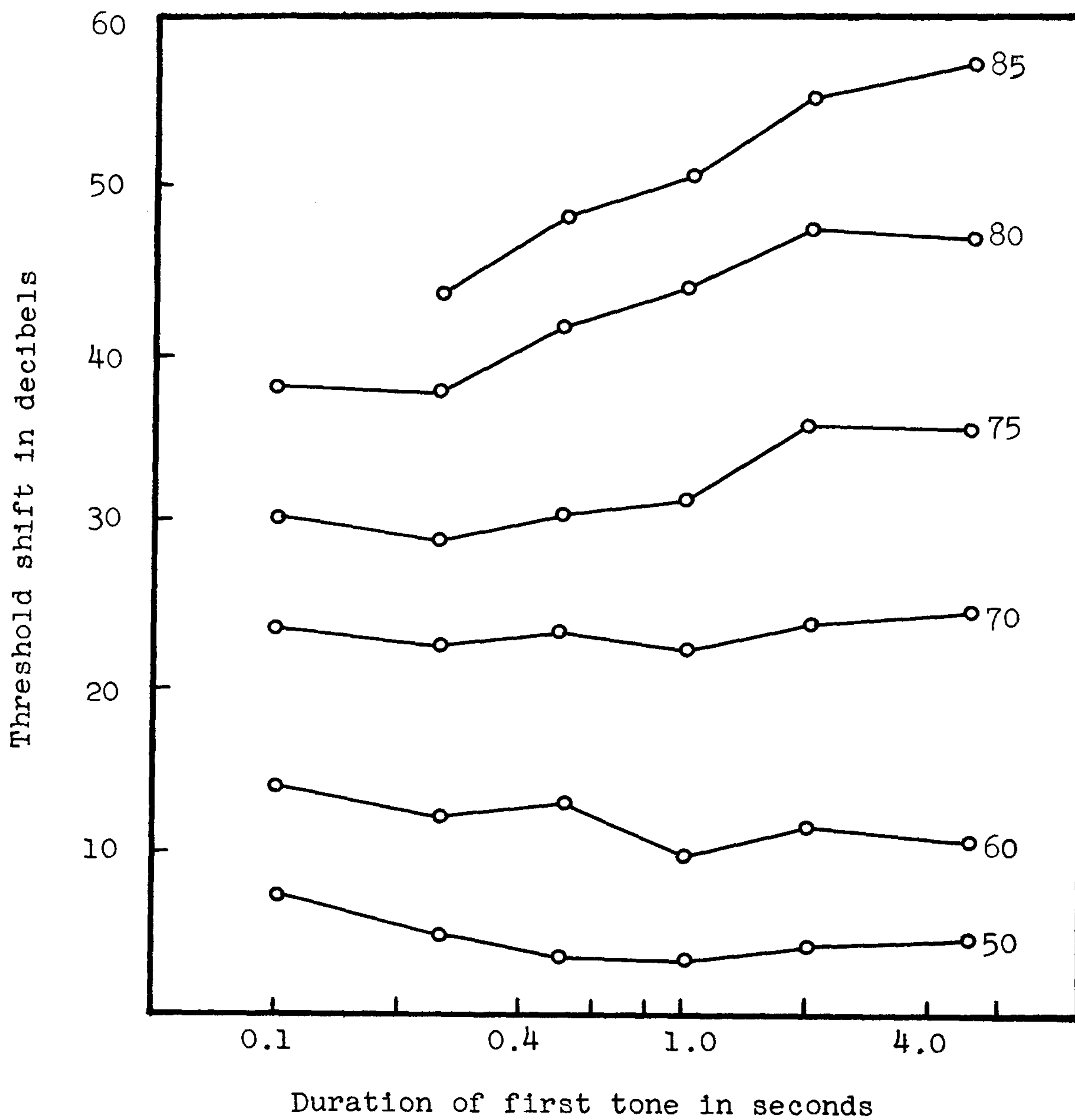
Once a certain stimulus intensity has been exceeded, the threshold shift for a given recovery interval seems to become sensitive to the duration of exposure (see Fig. 17.1).

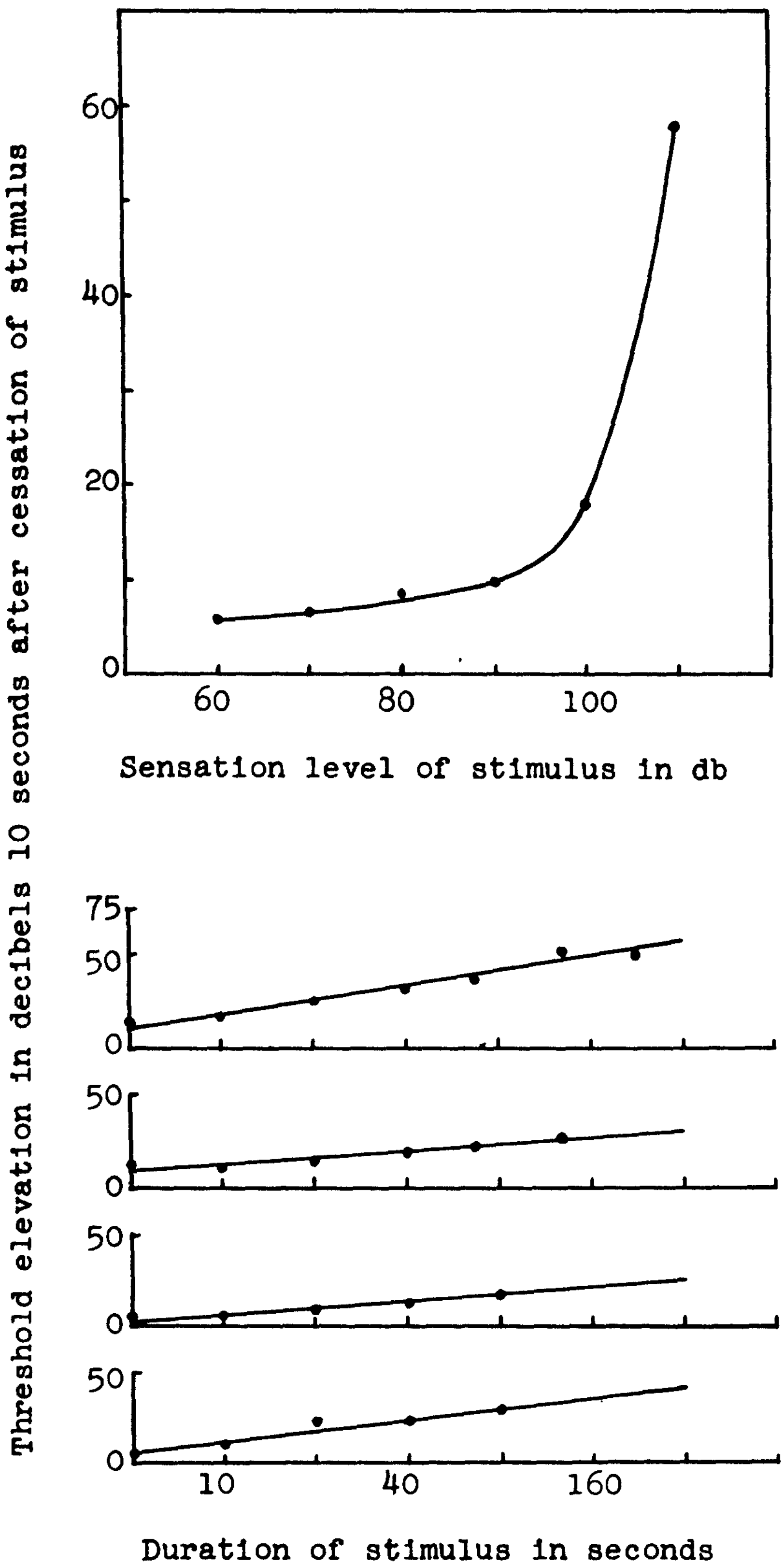
As we increase both intensity and duration of the exposure stimulus (we are now dealing with seconds or minutes and not with fractions of seconds) further, the threshold shift at a given recovery interval increases suddenly (see Fig. 17.2A). The bend in the curve does not seem to occur at the same stimulus intensity on even the same sensation level for all subjects but it seems to make its appearance somewhere in the vicinity of 90 db sensation level. For such stimulus intensities the pattern of the pure-tone threshold as a function of frequency changes in character. While previously (for very short recovery intervals) the maximum effect was found at the frequency of exposure, the maximum threshold shift for considerably longer recovery intervals has shifted upward in frequency.

This characteristic asymmetrical pattern with practically no loss at frequencies lower than the exposure frequency (sometimes accompanied by sensitization at the exposure frequency itself) has been dignified by the name of "half-octave low". According to this rule, the greatest hearing loss occurs at about 1/2 octave above the exposure frequency; hearing loss may, however, extend as much as 3 or even 4 octaves above the exposure frequency. The fact that at some time during recovery the maximum loss is found 1/2 octave above the exposure frequency does not imply that it will in the further course of the recovery remain tied to this frequency.

Figure 17.1

Effect of duration of exposure tone (500 cps) upon the threshold shift of a 1000 cps tone pip of duration 30 milliseconds. The silent interval between tones is 20 milliseconds. The figures to the right of the curves are the parametric values of the sensation level of the exposure tone. (After Rawnsley and Harris 53/).


60
50
40
30
20
10
Threshold shift in decibels
85
80
75
70
60
50
0.1
0.4
1.0
4.0
Duration of first tone in seconds



Threshold elevation in decibels 10 seconds after cessation of stimulus
60
40
20
0
60
80
100
Sensation level of stimulus in db
75
50
0
50
0
50
0
50
0
10
40
160
Duration of stimulus in seconds

What happens as we further increase the SPL of our exposure stimulus as well as its duration? Laboratory experimentation tells us of the effects of exposures up to 140 db SPL at durations up to about one hour. Most of the data are to be found in the Ruedi and Furrer 42/ and Davis et al 43/ monographs. As we might anticipate, such exposures result in severe temporary hearing losses from which subjects recover after a few hours, days or weeks.

Where, will the reader ask, is the point of no return, i.e., where will the induced hearing loss no longer remain entirely temporary? For rather obvious reasons we do not have the answer to this question. Few are the subjects who can testify to the fact that irreversible threshold shifts can be acquired in the laboratory. Responsible experimenters watch out for such things. But even if a few such cases occurred, who could tell which of a series of exposures broke the inner ear's back? Cumulative effects should certainly not be overlooked in such a situation.

It is almost intuitively clear that there exists something like an elastic limit, i.e., a SPL that once exceeded produces irreversible changes in a subject's ears. For man data are scarce, but the region is apparently somewhere above 155 db. For anesthetized animals it may be closer to 150 db SPL.

Figure 17.2

A. Threshold shifts as a function of stimulus intensity after a one minute exposure to a 2048 cps tone. Data points represent averages for three subjects. Recovery is tested at the frequency of the exposure stimulus.

B. Threshold shifts as a function of the duration of exposure for four different subjects. Exposure tone and test tone again have the same frequency (2048 cps). The sensation level of the exposure tone was 100 db. (After Hood 45/).

While we can conceive of such a limit as something almost almost independent of the duration of the exposure, we are at an almost complete loss when asked to specify what kind of an intensity-time relation we suggest for an "equinoxious" contour. We feel that we are safe in saying that the higher the SPL (below the critical limit) the shorter the exposure time necessary to produce irreversible effects. We have little faith that a linear relation for such effects will exist as is shown in Fig. 17.2B for reversible effects.. As a matter of fact, other authors, using average hearing loss throughout a certain frequency range as an indicator of the temporary damage, disagree with the findings represented by 17.2B. Too many uncontrolled factors exist in the picture of the development of permanent partial deafness to permit us to apply a simple I x t rule.

The question is often asked: What is the relation between the temporary (reversible) losses that can be produced in the laboratory and the permanent (irreversible) effects observed in industry, for instance? Is the same process at work in the two situations? The preceding description of the effects of exposure emphasized both the continuity of the phenomena and the changing character as the exposures grew more severe. We shall refrain from making the superficially simple assumption that all throughout the auditory range there is only a single exposure-recovery process at work. We shall also refrain from making assumptions as to where in the inner ear this single process is to be found. We need a good deal more information before such queries can be answered meaningfully. The mere fact that inter-observer variability in threshold shift increases as exposures become more severe, added to the fact that different observers recover very differently from what is apparently the same loss, invites caution.

In view of the variability among individuals and the great number of uncontrolled factors, the whole matter should be treated statistically. In Sec. 18.4 we have attempted an empirical approach to this problem by trying to establish a damage risk criterion for the control of noise.

Another gap in our knowledge needs to be filled before we tackle the problem of the relation of reversible to irreversible threshold shifts. Most of the studies of temporary loss used pure tones as exposure stimuli. The few data on exposure to noise (Davis et al 43/, Postman and Egan 56/) or to complex sounds (Ruedi and Furrer 42/) do not provide enough continuity between laboratory experiments and actual exposures in industry.

On several occasions we have referred to the truly amazing amount of variability that seems to exist among individuals with respect to both permanent and temporary losses. Audiometric examinations of workers in noisy industries show time after time that, out of a group of men who have apparently been exposed to the same noise, some will show marked symptoms of deafness, while the hearing of others will remain practically normal, even after conditions of severe exposure. There is at present no good rationale for these facts. They just have to be accepted.

Peyser 57/, Wilson 58/, and more recently Theilgaard 40/ have tried to design predictive tests on the basis of which noise-susceptible individuals could be separated from others. Theilgaard's results represent the most comprehensive investigation with pure tones as exposure stimuli. Unfortunately, his results are not encouraging.

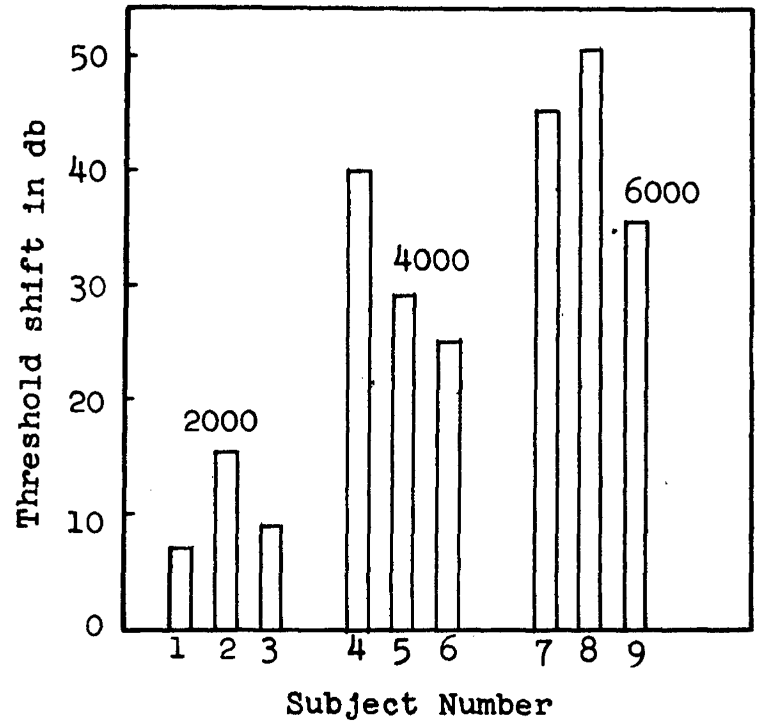
Theilgaard finds that not only is there variability between subjects, and between exposures for a single subject, but there is also striking variability between the effects of exposure upon the two ears of the same subject. (Wheeler 59/ confirms this finding.) There is even an indication that susceptibility to noise-induced hearing loss may change with frequency in the same individual. Theilgaard concludes that there is no reason to assume that a generally valid prediction for a person's susceptibility to noise can be based upon the amount of temporary loss found at one frequency.

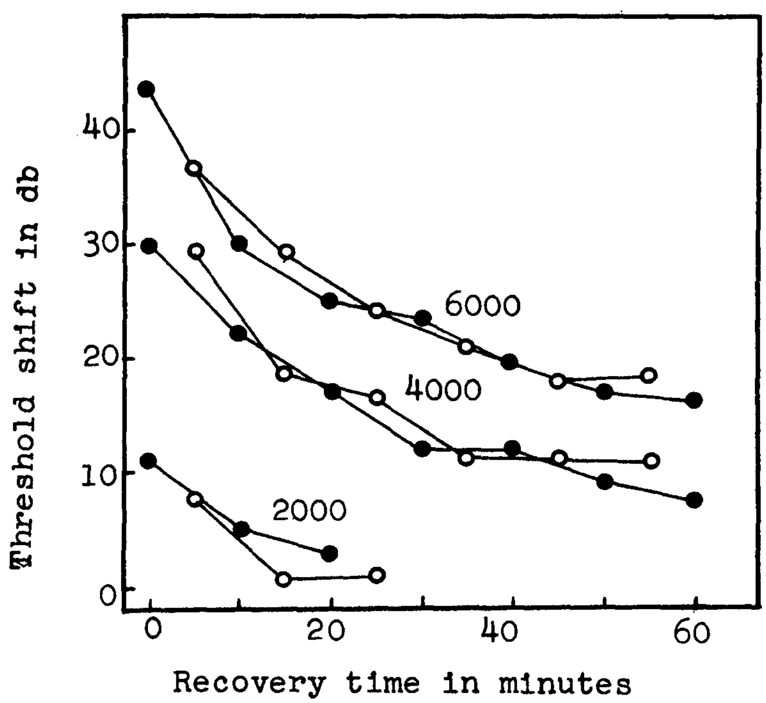
Wheeler 59/, in this country, has also worked on the problem of the desirable characteristics for a practical predictive test. Figure 17.3 shows some of the results he obtained. Wheeler expresses his preference for a complex noise as the exposure stimulus. He suggests that the test frequencies be confined to the high frequency region, and that the criteria of susceptibility be based upon both initial threshold shifts and rate of recovery. Wheeler points out that even if we decided today upon a standardized predictive test we would not know how far we could really trust it. The validation procedure would require years of follow-up studies in industry.

Figure 17.3

A. Initial threshold shifts at different frequencies, observed after exposure to 30 minutes of thermal noise at 105 db SPL. The exposure stimulus was delivered over a loudspeaker. Each bar represents the mean of three exposures for a different subject.

B. Recovery curves for nine subjects (three at each frequency). Open circles are threshold shifts for right ears, while solid circles indicate threshold shifts for left ears. Each experimental point is the mean of nine post-exposure thresholds. (After Wheeler 59/)


Threshold shift in db
0
10
20
30
40
50
2000
4000
6000
1 2 3
4 5 6
7 8 9
Subject Number


Threshold shift in db
0
10
20
30
40
6000
4000
2000
0
20
40
60
Recovery time in minutes

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CHAPTER 18

HUMAN RESPONSE CRITERIA FOR NOISE CONTROL

18.1 Introduction: The Establishment of Engineering Criteria for Noise Control

In the preceding chapters we have tried to assess the effect of sound on various aspects of man's behavior. In Chapters 16 and 17 we have been concerned with both psychological and physiological functions. We have seen how only too often we are rather far from a complete understanding of the interaction between sound and man. In some areas the basic information is available and we have only to plug in particular values* in order to predict just how man's actions will be affected. In other areas, particularly those concerned with the effect of what we might call "very intense sound indeed," we are relatively ignorant of the basic non-auditory phenomena. There is some hope, however, that the next few years will witness an accumulation of reliable data in this field whose importance from the viewpoint of military effectiveness is scarcely in doubt.

We have also tried to point out that even in the areas in which the basic information is available there is still often considerable variability among individuals, with the exception perhaps of the problems involving speech communication. In many instances we are unable to predict how a given sound will affect a particular individual. This means that we are not yet ready to select people for a given job in a manner that will realistically take into account their individual susceptibility to sound.

But when all these warnings have been given, when all the qualifications have been put down on paper, the fact remains that people have to make decisions in this area that involves the interaction of noise and man. Some people have the responsibility for deciding where a given airfield is to be located; others have to make sure that speech communication

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* An example is a situation in which a specifiable masking noise interferes with the reception of a specifiable sound. Figure 16.17 summarizes one of the instances for which a satisfactory generalization or computational scheme exists.

will be possible at a certain distance from a jet engine running at full power; still others have to persuade some of their fellow workers of the necessity of wearing ear protection. This dilemma could be paraphrased - with apologies to Emerson - "When theory whispers low, 'you can't', practice replies, 'I must!'"

Under such circumstances there is a temptation to base all judgments upon a single criterion (overall sound pressure level, or loudness, for instance) and to make decisions that one would assume to be at least consistent if nothing else. Unfortunately there are no single magic numbers that permit us to arrive at policy decisions with respect to noise control.

As we have seen in our previous discussion, "noise" is basically unwanted sound, i.e., sound that interferes with an activity that we want to carry on. However, that interference has to be specified. A given sound is not equally effective in masking speech, in interfering with sleep, or in producing permanent hearing loss.

In recent years there has been a growing tendency to assess the effect of a noise by its loudness. We have seen in Sec. 16.2 that it is by no means simple to arrive at loudness judgments for sounds having a complex spectrum and a rather irregular character in time. But let us assume that by some carefully worked out procedure we should be able to overcome these difficulties. We will still be faced with the fact that loudness functions are not related in the same way to such functions as masking, hearing loss, or even speech intelligibility.

Your intuitive feeling may be that all you really object to when you hear a noise is its loudness. In the face of this quite common reaction let us make our position more precise. Given a noise that interferes with speech communication in a quantifiable way, the same noise made louder (or more intense) will interfere more with speech communication. In other words, as long as we are not changing noises or human functions in mid-stream we can assess the interference caused by a noise by quantifying it as a function of its loudness. If, however, we are interested in hearing loss after exposure to the noise and not in masking of speech we can not offhand assume that we are still dealing with the same function. And if we are concerned with a different noise, we have to make sure that the old noise and the new noise can be judged on the same loudness scale without obtaining paradoxical results.

It is apparent, then, that we have to establish about as many sets of criteria as there are human responses in whose performance we are interested. And that we have to specify in a rather detailed fashion the noise that is interfering with a given response. Let us not give up hope that in the course of time we shall be able to generalize our results. At present let us aim toward using the criteria we have suggested as framework in which data can be usefully collected and evaluated.

We shall be concerned primarily with the interference of noise with three general types of response or behavior. People want (1) to live in their homes without being too much disturbed by noise; (2) to communicate with each other by speech, and, (3) to protect their ability to hear. There are, of course, situations in which the response is not easily broken down into definite units of behavior. In such instances, the setting of criteria becomes singularly difficult.

18.2 Criteria for Residential Living

Introduction. In and around our homes we are constantly exposed to noise that originates from sources both indoors and outdoors. The level of the noise is often quite low, but it is rarely inaudible, even in the most remote suburban areas. Frequently the sounds are virtually unnoticed, i.e., we hardly react to them, and we accept them as part of our environment. The noise from distant traffic, the occasional passing of an aircraft at a distance of 5000 ft or more and the noise of falling rain, rustling leaves and crickets all belong to the general category of "ambient background noise" for a large majority of people. Frequently, however, a noise that is unwanted or annoying, to some residents at least; intrudes through the background noise. Acoustical engineers are often faced with the problem of predicting the probable neighborhood reaction to the noise on the basis of physical measurements of the noise. Their task may be to prescribe measures for reduction or control of the noise at the source so that it does not give rise to expressions of annoyance on the part of the residents, or so that it is at least tolerated by them.

There are essentially two aspects to the analysis of the interaction between an intruding noise and human beings exposed to the noise. The psychologist would call these aspects stimulus and response. The stimulus function can, as a first approximation, be defined by a physical description of the

noise to which the human beings are exposed. It may, however, also be necessary to describe the physical characteristics of noises to which a particular group of people have been exposed in the past, in order to evaluate the degree to which they have become adjusted to a noisy environment. The response of residents is measured through expressions of annoyance, complaints or even through legal action. Our task here is to be able to predict their response from knowledge of the stimulus function, past and present.

In all questions involving the interaction of noise and man we must be careful to state the type of behavior that is involved. In the present analysis it has been assumed that the intruding noise interferes with a generalized class of behavior that may be described as "residential living." The scheme cannot be applied directly to cases that involve noise in the vicinity of hospitals or that primarily involve interference with speech communication (in the classroom of a school in a residential area, for example). Interference with speech, sleep and various other occupations and avocations (such as listening to music) is involved only in the sense that such functions are part of residential living.

Ideally, an adequate description of the stimulus should provide a quantitative specification of all characteristics that are likely to influence response behavior. It is clear that many variables are involved. Two important variables are the overall sound pressure level and the frequency spectrum of the intruding noise. Other typical factors influencing the response are the repetitive character of the noise, the time of day or night at which the noise occurs, the history of the previous exposure to noise and the origin of the noise. Often certain aspects of the stimulus are best described in statistical terms, since some of the variables involved may fluctuate over a range of values.

In the following analysis, a scheme is proposed to permit the evaluation and correlation of a certain number of relevant data relating to both stimulus and response. The scheme results in a specification of the stimulus in terms of a noise rating, a single number that should enable the acoustic specialist to predict the statistical range of neighborhood reaction to the noise. Case histories and field data involving neighborhood reactions to noise are cited as justification for the proposed scheme.

It must be emphasized that the scheme presented here is largely empirical, and that it should be regarded as one of the several possible frameworks within which data from case histories could be correlated. It is clear that there are many limitations, and the procedure is subject to revision and refinement as further data become available.

In effect, the proposed framework provides us with a set of criteria for the control of noise in residential areas. In the establishment of such criteria, a decision must first be made concerning the acceptable level of complaints from the community. Then the empirical scheme to be described indicates to what extent the noise must be reduced or modified in order that the complaints be kept below this acceptable level.

The Noise Rating. A study of evidence that has accumulated over the years has led us to the conclusion that there are at least seven largely independent characteristics of a noise stimulus that control the response behavior of a community exposed to the noise. The role played by each of these seven variables in contributing to a final evaluation of a so-called noise rating is discussed in the following paragraphs. In general the noise rating of a stimulus determines the statistical range of responses to the stimulus. In addition we shall discuss certain other factors that are likely to modify the response of a neighborhood but which are usually important only in rather special or unusual situations.

Level Rank. The overall level and the spectrum of the noise are of primary importance in the determination of the noise rating. In the present analysis, the spectra are assumed to be given as sound pressure levels in octave frequency bands. It is assumed that the values are obtained by averaging over a reasonable length of time (similar to the averaging performed by a standard sound level meter) and over a reasonable number of locations in the community. Thus instantaneous peaks of sound pressure and levels in localized regions of somewhat higher or lower intensity than the average are smoothed out. The spectra may be obtained: (a) by direct measurements with a sound level meter and octave band analyzer, or (b) by calculations derived from engineering data on noise sources and transmission properties of the relevant media. Techniques of measurement and data from which one can perform such calculations are discussed in Volume I.

Figure 18.1 shows a family of curves that define the "level rank." The ranks are designated by the letters from A to M. We are using the letters of the alphabet as an appropriate rank order scale for our level ranks. This should make definitely clear that D is a higher rank than B, since D comes later in the alphabet. Had we chosen the natural numbers to designate our level rank, one might be tempted to assume that a noise having a level rank of 4 was twice as annoying as a noise having the level rank of 2. This is precisely what we wanted to avoid. We feel that all we can specify is rank order plus, perhaps, a crude scale of equal intervals, each of them having a value of approximately 5 db.

Each rank is associated with the area between two neighboring curves. At the low end is rank A, and the lower boundary of this rank is a smoothed curve representing the average threshold of hearing (free field). The highest rank is M and the upper boundary of this rank approaches the currently used criterion of damage to the hearing mechanism under continuous exposure. (See Sec. 18.4). This choice of scale implies that a noise that is inaudible does not contribute to annoyance and that a noise that may produce permanent damage to the unprotected ear would in any case be treated as socially unacceptable whether or not questions of annoyance are involved.

The measured or calculated octave band spectrum of the intruding noise is to be superimposed on Fig. 18.1. The level rank of the noise spectrum is given by the highest area into which the spectrum intrudes in any band. This procedure implies that the noise level in a single band (the one projecting into the highest area in Fig. 18.1) can in some cases determine the level rank uniquely. Essentially, the assumption is that different frequency bands contribute independently to the shaping of the response, and that the effects of different bands are

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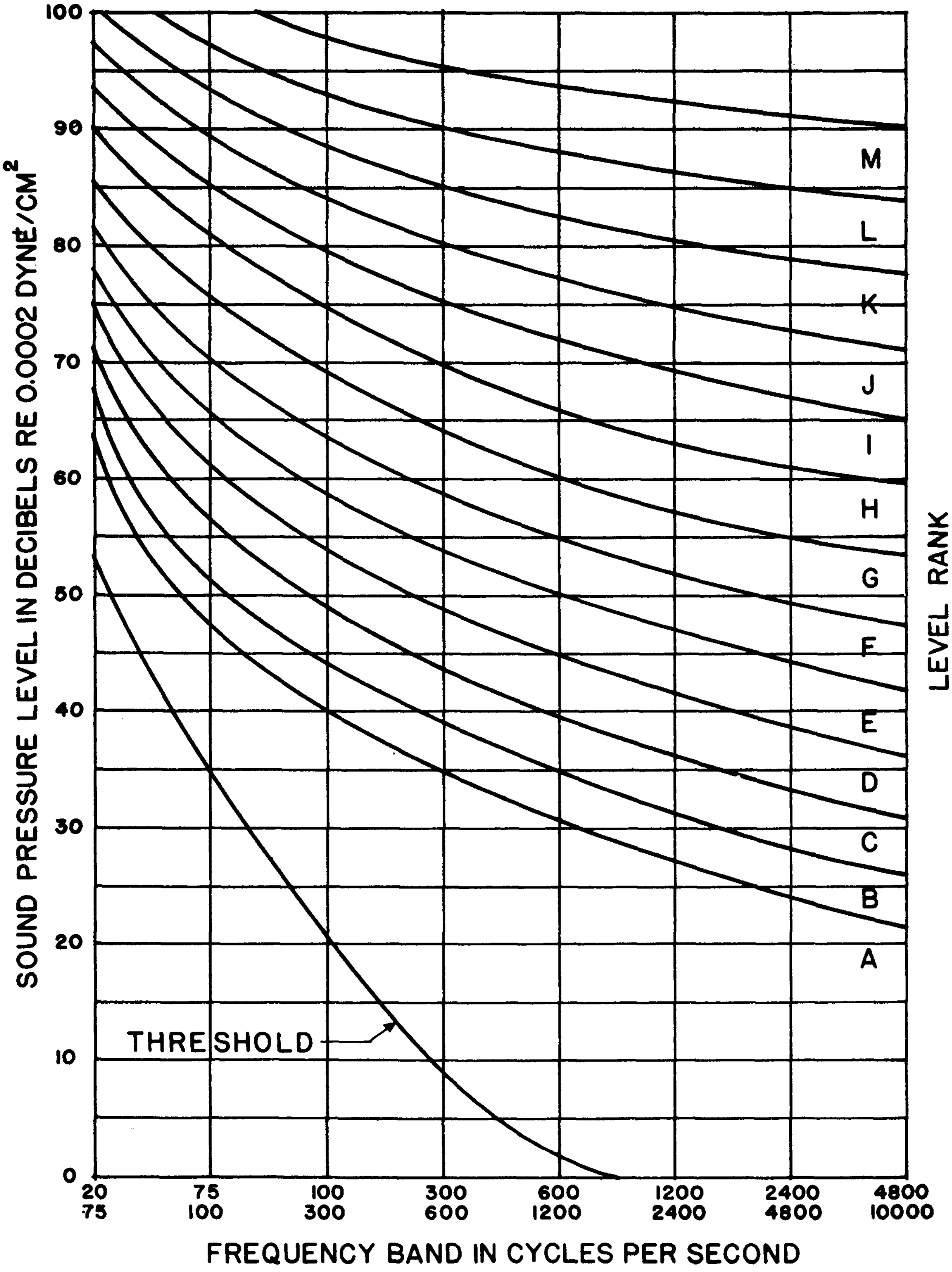
Figure 18.1

Family of curves used to determine the level rank for residential noise. The spectrum of the noise is plotted as sound pressure levels in octave bands of frequency. The highest zone into which the spectrum protrudes is designated as the level rank of the noise.


100
90
80
70
60
50
40
30
20
10
0
SOUND PRESSURE LEVEL IN DECIBELS RE 0.0002 DYNE/CM²
M
L
K
J
I
H
G
F
E
D
C
B
A
LEVEL RANK
THRESHOLD
20 75
75 100
100 300
300 600
600 1200
1200 2400
2400 4800
4800 10000
FREQUENCY BAND IN CYCLES PER SECOND

not additive. At present, no laboratory data are available for substantiation of this assumption. However, we shall note later that the case histories provide data that are not inconsistent with the above assumption, and for the present this is considered as adequate justification.

The justification for selecting the particular curves shown in Fig. 18.1 lies primarily in the evidence obtained from the case histories cited later in this section. A few remarks are pertinent at this point, however. There is reason to believe that the loudness* of a given band of noise is correlated to some extent with the annoyance it produces. Using 250-mel bands of noise as stimuli in laboratory experiments Kryter 1,2/ and Pollack 3/ have shown that subjects tend to judge equally loud stimuli to be equally annoying, except at very high and low frequencies. It happens that the boundary lines between ranks in Fig. 18.1 represent noise spectra which have approximately equal loudness in equal mel bands, assuming free-field listening. Loudness data for continuous spectrum noise do not extend below 100 cps. The shape of the curves at low frequencies represents an empirical extrapolation. Thus some justification for the shape of the curves is provided in addition to evidence from field data.

The distance between neighboring curves in the mid- and high frequency range is approximately 5 db. The steps are slightly smaller at low intensities and somewhat larger at high intensities. At low frequencies the spacing between curves is decreased, as the bunching of the equal loudness contours for bands of noise at low frequencies would suggest. Several considerations dictate the selection of 5 db as a suitable discrete step for the specifications of level rank. From previous experience, it is believed that the range of variation normally encountered in the reactions of the residents of a community to a given noise is sufficiently wide that a change of noise level of less than 5 db would not produce a significant change in the general pattern of reaction to the noise. In many situations, also, the fluctuations of the noise levels both in time and in space within a community are as high as 5 db, and it is unrealistic, therefore, to specify the levels with greater precision.

Correction Numbers. Once the level rank has been established by the procedure outlined above, attributes of

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* See Section 16.2

the noise other than the average level and the spectrum must be evaluated in order to arrive at the final noise rating. This evaluation takes the form of correction numbers. These correction numbers are the number of ranks by which level rank is increased or decreased. The final result of this calculation is the composite noise rating. The evaluation of the correction numbers is discussed in the following sections. A summary of all correction numbers is presented in tabular form following the discussion.

1. Spectrum Character. A noise spectrum that contains audible pure-tone or single-frequency components appears to be more annoying than a spectrum that is reasonably continuous. This deduction is based upon engineering experience with noise spectra of both types. If, for example, the sound pressure level in an octave band reaches the level rank D by virtue of the contribution of a single frequency component, it is proposed that a rank correction of value +1 be applied, i.e., that the level rank of the noise be raised from D to E. For a continuous spectrum noise, no correction should be applied. The implication is that, all other things being equal, the level of a pure tone must be about 5 db below the level of a continuous spectrum noise in the same octave band in order to produce the same neighborhood reaction.

2. Peak Factor. A noise that is reasonably continuous in time, at least over periods of a few seconds or more, is assumed to be less annoying than an impulsive type of noise An example of impulsive noise is the sound from a drop forge or gun shots. In the proposed scheme a level rank correction of value +1 should be applied to the level rank if the noise is impulsive, but no correction should be applied for a continuous noise. At present no firm definition of an impulsive type of noise in quantitative terms is proposed, and some judgment is required to distinguish between impulsive and continuous noise.

3. Repetitive Character. In addition to the short-time peak factor discussed above, the repetitive character of the intruding noise influences the neighborhood reaction to a large degree. For example, a noise that lasts for 20 seconds during every minute is judged to be more annoying than the same noise occurring twice a day. A community will tolerate the occasional passage of a jet aircraft overhead, but frequent passage of such aircraft may lead to strong complaints. Quantitative evaluation of the influence of repetitive character is not well established at present because field data are not available for

a wide range of conditions. Assuming exposures of 20-30 seconds duration (the approximate time during which the sound from an aircraft overhead can be heard), Table 18.1 gives some preliminary estimates of the correction numbers to be applied numerically to the level rank. For exposures of different duration, a good deal of judgment is necessary in selecting the appropriate correction number. No correction is to be applied for a noise that is continuous.

TABLE 18.1

CORRECTION NUMBERS TO ACCOUNT FOR REPETITIVE CHARACTER OF NOISE, 20-30 SECS EXPOSURES ASSUMED

1 exposure per min (or continuous)	0
10-60 exposures per hour	-1
1-10 exposures per hour	-2
4-20 exposures per day	-3
1-4 exposures per day	-4
1 exposure per day	-5

This table is clearly very tentative. Here, as elsewhere, we do not have the necessary number of cases to tie down the correction parameters the way we have indicated. As more case histories are checked against this scheme, it will turn out that certain correction procedures represent pretty good guesses while others are in need of modification.

4. Level of Background Noise. The level of background noise is usually lower in suburban communities than in urban areas (see Ch. 8). In the city the average noise from traffic is greater and, especially in industrial areas, there are often contributions to the noise level from factory machinery and similar sources. Residents in areas with low background level are more likely to react to intruding noise of fairly low level than those in areas in which the background noise partially masks the intruding noise. Also, if a fairly high background noise exists, residents become adjusted to the intrusion of noise, and are less inclined to complain. In a sense, the background noise plays the role of a reference level with respect to which the intruding noise is measured.

On the basis of measurements of the levels of background noise in various communities, and on the basis of experience with complaints in these communities, the following correction numbers in Table 18.2 are proposed to account for the levels of background noise. These correction numbers are added to, or subtracted from, the level rank. Examples of the approximate range of background levels and spectra for the various communities are shown in Fig. 18.2 and approximate correction numbers are noted on the figure.

If we have a background noise spectrum different from the contours of Fig. 18.2 some judgment is required in estimating the appropriate correction numbers. In most areas, however, spectra similar in shape to those in Fig. 18.2 will be found.

TABLE 18.2

CORRECTION NUMBERS TO ACCOUNT FOR THE AMBIENT NOISE LEVELS IN THE NEIGHBORHOOD (SEE ALSO FIG. 18.2)

Neighborhood	Correction Number
Very quiet suburban	+1
Suburban	0
Residential urban	-1
Urban near some industry	-2
Area of heavy industry	-3

5. Time of Day. Most residents agree that intruding noise is more tolerable in the daytime than during the evening. During the night, the background noise levels from traffic and other sources are usually lower than the corresponding daytime levels and hence an intruding noise is subject to less masking. Therefore, the noise is more noticeable. We estimate that a correction number of -1 should be applied to the level rank if the intruding noise occurs only in the daytime. No correction is applied for round-the-clock operation or for operation after, say, ten o'clock at night.

6. Adjustment to Exposure. Experience has shown that residents can adjust to a varying extent to an intruding noise

after repeated exposures. For example, people near a railroad can become accustomed to the noise, even though they may be annoyed during the first few days of exposure. The noise of an occasional aircraft overhead is now accepted by most people, and they are considered, therefore, to be adjusted to this sound. No correction should be applied to the level rank if the intruding noise is a new one to which the residents have not been exposed previously. If there has been some adjustment to the noise, a correction number of -1 is proposed. Only in extreme conditions (such as emergency or wartime) should a correction number of -2 or more be applied. We are suggesting, therefore, that adjustment to exposure is worth 5 to 10 db.

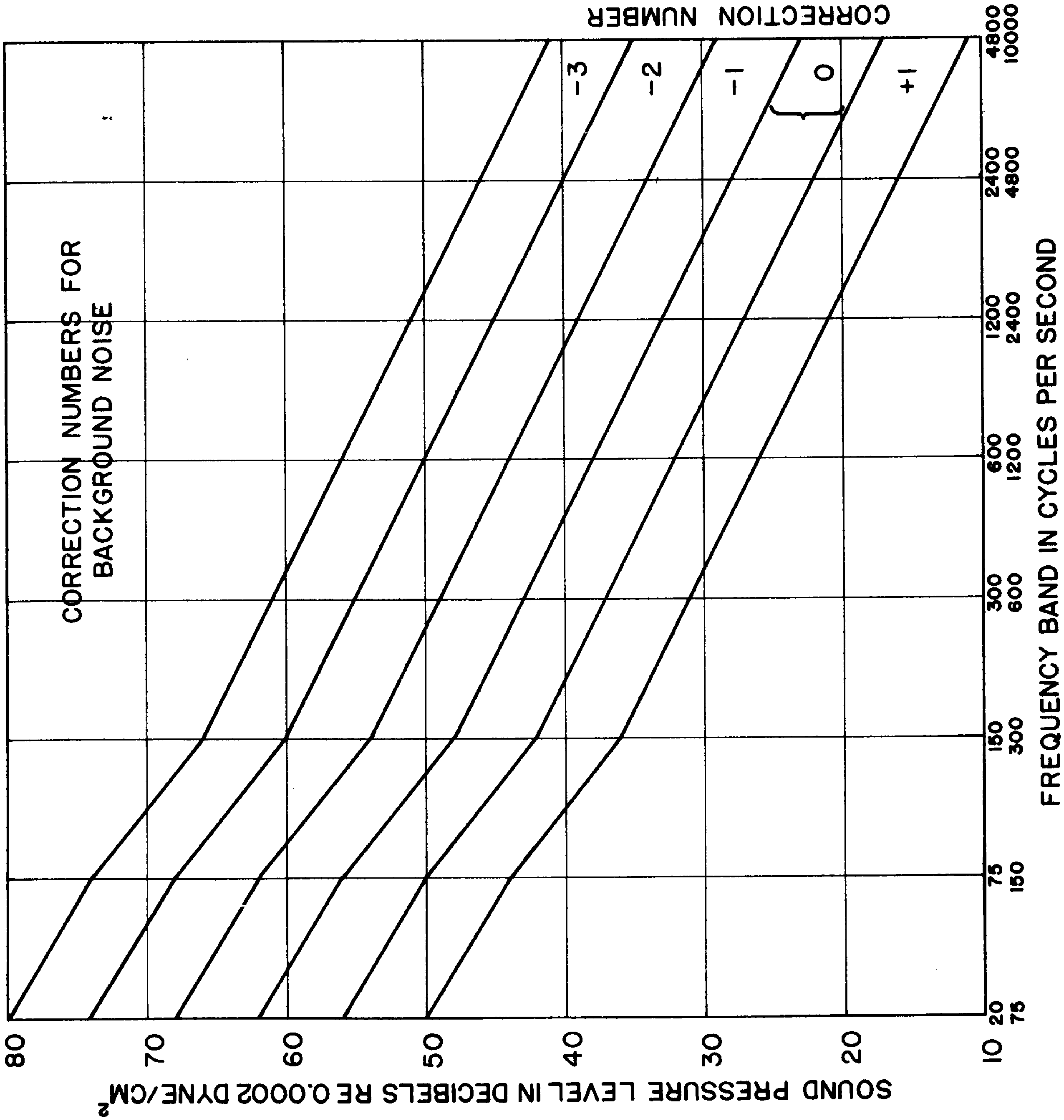
7. Other Factors. In addition to the physical factors listed above, factors of a psychological nature influence neighborhood reaction to an intruding noise, though by no means to a constant degree. Such questions as connotation of the noise and public relations between the community and those causing the noise may modify the noise rating to a marked extent. To account for these more subtle factors in a quantitative fashion is a difficult task.

For example, a statement in the press to the effect that a certain type of noise is damaging to the health of persons exposed to the noise could suddenly lead to strong adverse public reaction, even though the noise level remains the same and physical measurements of the noise might even indicate a low noise rating. Again, if an intruding noise carries the connotation of danger (for example, the noise of a low-flying aircraft, especially after some accidents have occurred nearby), residents are likely to react more strongly than they would to a noise of the same level but originating within their own home.

For some residents, the source of noise may be related

Figure 18.2

Family of curves used to determine the correction number for background noise. The spectrum of the ambient background noise is plotted as sound pressure levels in octave bands of frequency. The zone in which the major portion of the noise spectrum lies designates the correction number to be applied for background noise.


CORRECTION NUMBERS FOR
BACKGROUND NOISE
CORRECTION NUMBER
-3
-2
-1
0
+1
FREQUENCY BAND IN CYCLES PER SECOND
20 75
75 150
150 300
300 600
600 1200
1200 2400
2400 4800
4800 10000
SOUND PRESSURE LEVEL IN DECIBELS RE 0.0002 DYNE/CM²
10
20
30
40
50
60
70
80

to their job. Under such circumstances, they may be much more inclined to tolerate a certain noise level than if they considered the same noise as thoroughly unnecessary.

The present scheme for estimating neighborhood reaction to noise makes no attempt to account for these factors which are only indirectly related to the physical characteristics of the stimulus. Such factors appear, however, to be of major importance only rarely. Evidence of the existence of these factors should always be sought since occasionally it may be necessary to account for them in at least a semi-quantitative fashion.

Seasonal influences may modify the neighborhood reaction to noise. In the summer many residents leave their windows open a large part of the time and their exposure to a noise originating outdoors is likely, therefore to be more severe. On the other hand the meteorological and terrain conditions are, in many areas, more favorable for the propagation of sound in winter. Consequently the seasonal influences depend upon such factors as climate and distance from the noise sources to the residential areas. Thus it is difficult to state a general rule that is applicable in all cases. Terrain and meteorological conditions and their influence on sound propagation have been discussed in Chapters 9 and 12, respectively.

8. Summary. Table 18.3 summarizes the various physical characteristics of the stimulus and indicates the quantitative influence of each in the form of correction numbers that must be applied to the level rank to obtain the noise rating.

The level rank and the noise rating are identical for the case in which (1) the noise has a continuous spectrum, (2) it has a uniform short-time character, (3) it is continuous over long time intervals, (4) it is present at nighttime, (5) the acoustic environment is similar to that of a suburban community, and (6) there has been little previous exposure to the noise.

Relation between Response and Noise Rating. Having established the noise rating from physical measurements of the stimulus, we must next determine the expected response for each noise rating. The inherent assumption is that in the absence of dramatic events or particular psychological circumstances, stimuli that have the same noise ratings (although perhaps quite different level ranks) all produce the same response within a range of statistical variations. It is a

TABLE 18.3

LIST OF CORRECTION NUMBERS TO BE APPLIED TO LEVEL RANK TO GIVE NOISE RATING

Influencing Factor	Possible Conditions	Correction No.
Spectrum character	Continuous	0
	Pure-tone components	+1
Peak Factor	Continuous	0
	Impulsive	+1
Repetitive Character (20-30 Sec Exposures Assumed)	$>$ 1 exposure per min (or continuous)	0
	10-60 exposures per hr	-1
	1-10 " " "	-2
	4-20 " " day	-3
	1-4 " " "	-4
	$<$ 1 exposure per day	-5
Background Noise	See Figure 18.2	+1 to -3
Time of Day	Daytime only	-1
	Nighttime	0
Adjustment to Exposure	No previous exposure	0
	Considerable previous exposure	-1
	Extreme conditions of exposure	-2

truism that all residents do not react alike to a given stimulus. There is a distribution of responses, and it is necessary, therefore, to express the response in terms such as expected "average response," and "range of expected responses from a normal population."

The graph in Fig. 18.3 shows a relation that has been derived from empirical data. The response, stated in descriptive terms, is plotted as the ordinate, and the properties of the stimulus are given by the noise rating, which forms the abscissa.

The response scale is again a rank order scale. At the low end is the "no annoyance" region, which is defined as the region in which practically no residents are annoyed by the noise. This amounts to saying that residents do not consider the noise to be "intruding." Next is the region described by "mild annoyance." In this range residents are not likely to complain, say,to the management of the noisy factory, but they may comment on their annoyance among themselves. "Mild complaints" may be in the form of an occasional telephone call to the management. The next step on the scale of response is "strong complaints, which could be in the form of complaints to the management, to a newspaper, or to the police.. "Threats of legal action" may result if stimulus conditions are still more severe. The final category is "vigorous legal action." These last two terms are self-explanatory.

<u>Substantiation by Case Histories and Other Experiences</u>. The above scheme for the evaluation of neighborhood reaction to noise can be justified only by checking it against empirical data. The empirical data are in the form of case histories. We have, of course, used some of our case histories in setting up the scheme, and it is hardly conclusive now to use the same case histories to show the validity of the scheme. The real test for the scheme will come in the future when its ability to predict behavior of communities will be tested in new

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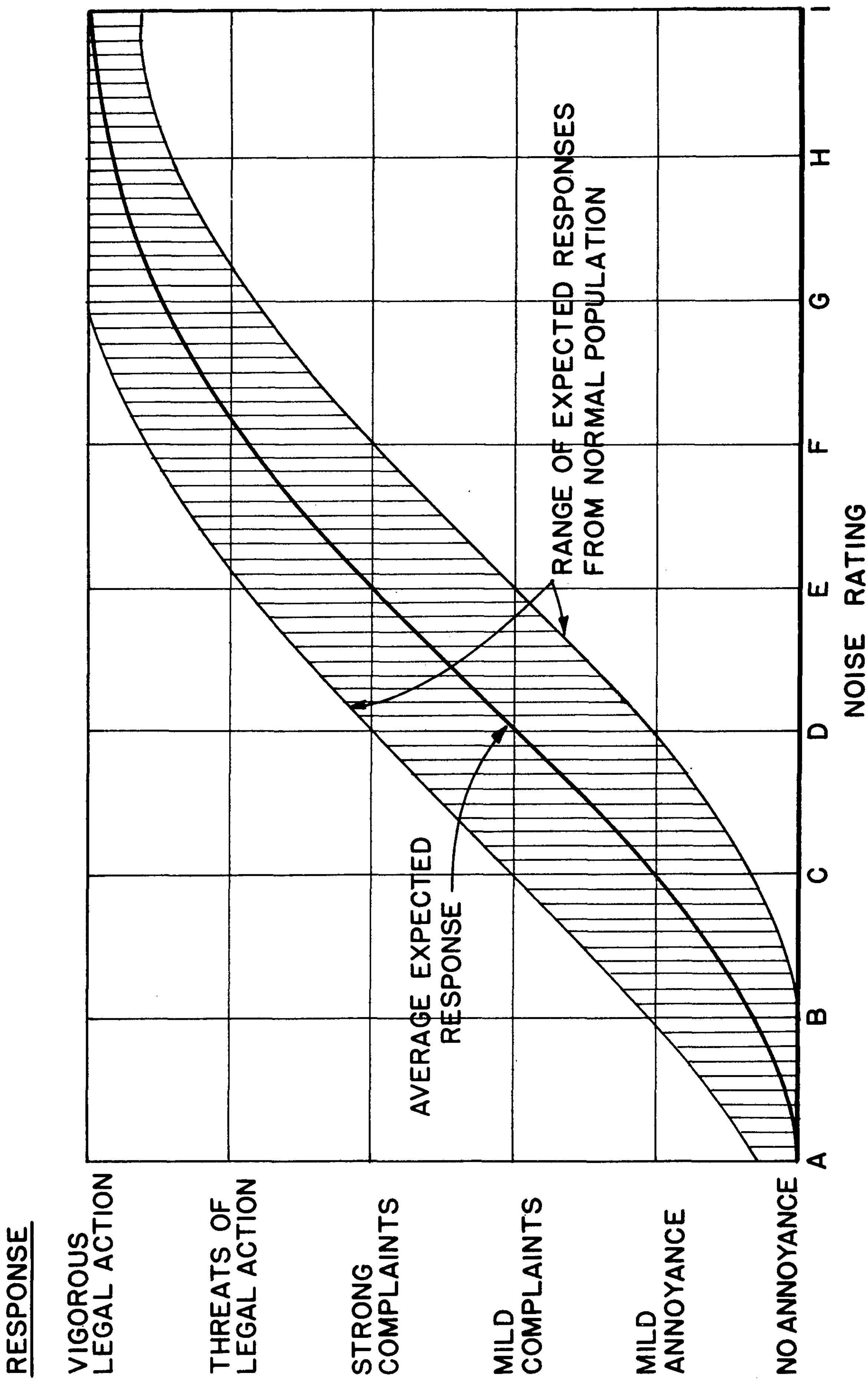
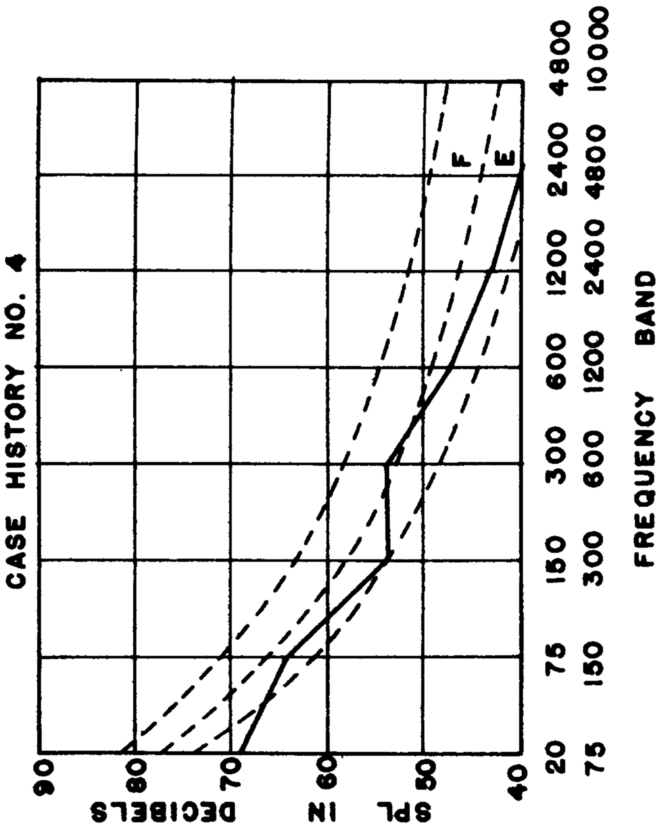
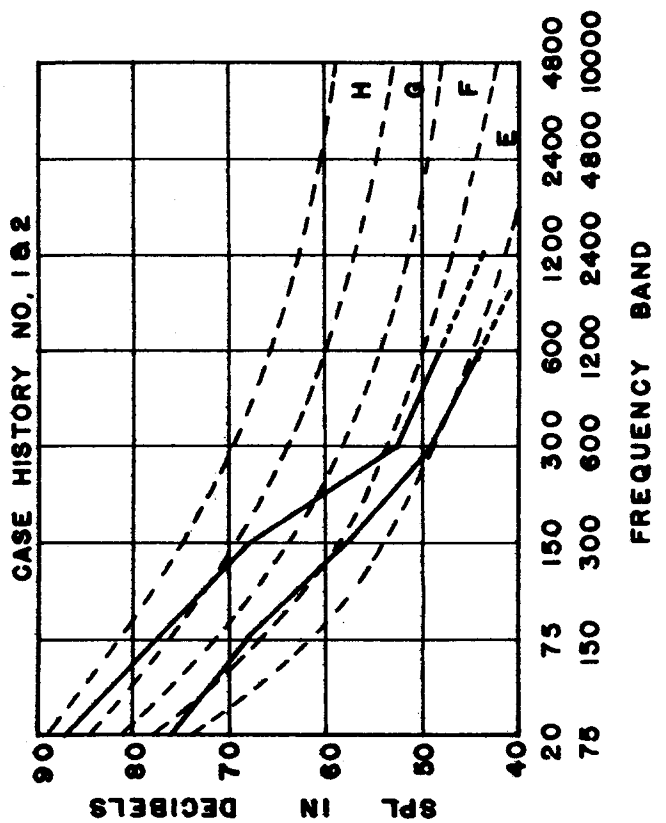
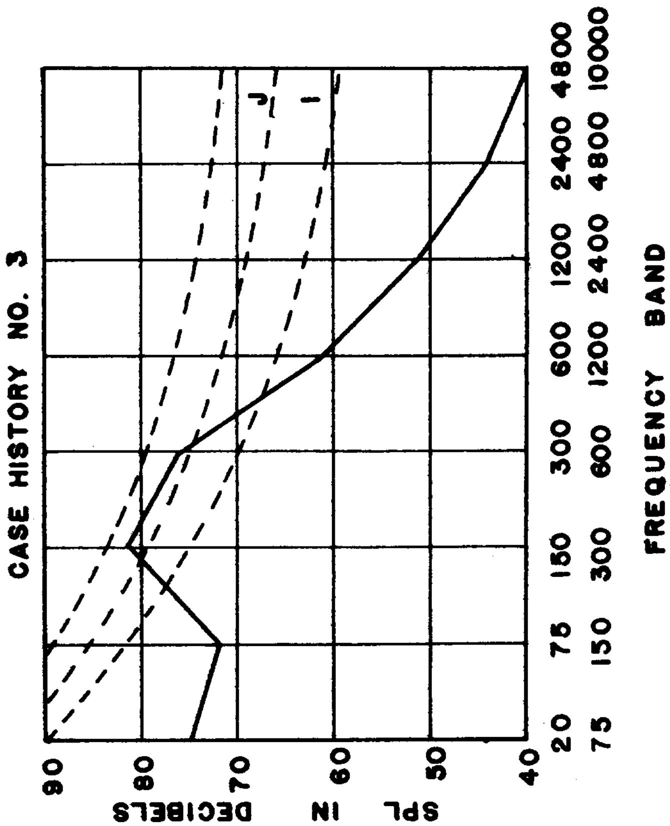
Figure 18.3

Relation between the composite noise rating and the response. The expected average response is shown, together with the expected range of variation.


RESPONSE
VIGOROUS LEGAL ACTION
THREATS OF LEGAL ACTION
STRONG COMPLAINTS
MILD COMPLAINTS
MILD ANNOYANCE
NO ANNOYANCE
AVERAGE EXPECTED RESPONSE
RANGE OF EXPECTED RESPONSES FROM NORMAL POPULATION
A
B
C
D
E
F
G
H
I
NOISE RATING


CASE HISTORY NO. 4
SPL IN DECIBELS
90
80
70
60
50
40
F
E
20 75
75 150
150 300
300 600
600 1200
1200 2400
2400 4800
4800 10000
FREQUENCY BAND


CASE HISTORY NO. 1 & 2
SPL IN DECIBELS
90
80
70
60
50
40
H
G
F
E
20 75
75 150
150 300
300 600
600 1200
1200 2400
2400 4800
4800 10000
FREQUENCY BAND


CASE HISTORY NO. 3
SPL IN DECIBELS
90
80
70
60
50
40
J
I
20 75
75 150
150 300
300 600
600 1200
1200 2400
2400 4800
4800 10000
FREQUENCY BAND

situations. In the meantime, the available case histories point up the spectrum of experience upon which this scheme was based, and hence also the type of situation it ought to be able to handle. We have summarized a number of case histories in which data from physical measurements of the stimulus are available, and in which some subjective data on neighborhood reactions are known.

We recognize, of course, that the available case histories do not cover a sufficiently wide range of conditions to substantiate the proposed scheme in all details. The selection of some of the correction numbers (such as those for repetitive character) is not based entirely on evidence from case histories, but may be based more on common experience and even "intuition." As further data are gathered, some changes in the scheme will be found necessary. Stimulus characteristics other than those considered here may prove to be important in determining the response.

Another limitation of the case histories is the uncertainty in the definition of the response in many cases. It is clearly impossible to obtain an adequate sampling of neighborhood reaction unless a well-controlled opinion survey is carried out. In most of the case histories described here, the specification of the response is based on verbal and documentary evidence obtained from the management of the facility that is responsible for the noise.

The evidence in the form of case histories is summarized in Table 18.4. All pertinent data concerning both stimulus and response are shown in the various columns of the table. For each case history the first column gives a brief description of the facility and the type of noise it produces. The level rank for the noise measured in the residential areas is indicated in Column 2. The spectra for some of the cases are shown in Fig. 18.4. The various correction numbers are indicated in Columns 3-8, and the composite noise rating is

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Figure 18.4

Measured spectra of intruding noise for four of the case histories listed in Table 18.4. The dashed lines indicate the boundaries of the level ranks, from Fig. 18.1. In each case, the level rank is the highest rank into which the noise spectrum protrudes.

TABLE 18.4

SUMMARY OF CASE HISTORIES OF RESPONSES TO NOISE IN RESIDENTIAL AREAS

	1	2	3	4	5	6	7	8	9	10	11
No.	Description of Facility and Noise	Level Rank	Spectrum Character	Peak Factor	Repetitive Character	Background Noise	Time of Day	Exposure Adjustment	Noise Rating	Predicted Average Response	Actual Response
1	Large wind tunnel in mid-west	H	0	0	0	0	0	0	H	Vigorous legal action	Municipal authorities forced facility to shut down
2	Large wind tunnel in mid-west	F	0	0	0	0	0	0	F	Threats of legal action	Vigorous telephone complaints and injunction threats. Management took immediate steps to lessen noise.
3	Exhaust for air pumps, factory in indus. area	J	0	0	0	-3	-1	-1	E	Strong complaints	Lodging house owner entered complaints with client and with local Dept. of Health
4	Engine run-ups Aircraft Mfg. Plant	F	0	0	-1*	0	-1	-1	b	Less than mild annoyance	No complaints reported by management. Operations restricted to daytime only.
5	Airport ground run-ups	F	0	0	0	0	0	-1	E	Strong complaints	Complaints by civic organizations, individual telephone calls and letters of complaints.

6	Aircraft in flight near airport	H	0	0	-2	0	0	-1	E	Strong complaints	Vigorous complaints by letter and telephone. One town attempted to prevent passage of aircraft.
7	Aircraft engine mfg plant test cells	F	0	0	0	-1	-1	-1	C	Mild annoyance	No complaints reported for daytime operation; a few for operation after 11 p.m.
8	Loading platform with trucks, men shouting, etc.	G	0	0	-1*	0	0	0	F	Threats of legal action	Vigorous complaints to management. Acoustical consultants called in by firm.
9	Transformer noise in very quiet res. area	F	+1	0	0	+1	0	-1	G	Between threats of legal action and vigorous legal action	Injunction threats
10	Large fan at power company; single freq. components	E	+1	0	0	0	0	-1	D	Strong complaints	Residents complained consistently, consultants called in to advise on noise control.
11	Weapons range, intermittent firing, 3-sec bursts several times per day	L	0	+1	-5*	-1	-1	0	F	Threats of legal action	Vigorous complaints from nearby residents for winter operation.

* estimated

evaluated in Column 9. The average predicted response, from Fig. 18.3 is noted in Column 10. Column 11 gives a brief description of the neighborhood reaction that was actually encountered. Comparison of Columns 10 and 11 indicate fairly good agreement between the predicted and the actual response in all cases.

Let us examine Case History 4 as an example. At a large aircraft manufacturing plant, with attached airport, maintenance checks are run intermittently on two-engine reciprocating aircraft during the daytime hours before 10:00 p.m. The duration of a run-up may be as high as 15 minutes and a correction number for repetitive character is set, therefore, at -1 (one rank lower than continuous noise). In the nearby residential areas no complaints are submitted to the management of the company. Presumably the residents have become somewhat adjusted to the noise, and many of them are employed by the company. The average spectrum of the noise in the residential area is shown in Fig. 18.4. Computation of the noise rating is shown in Table 18.4. It is of interest to note in this example that, according to Fig. 18.3, mild complaints to the management would be expected if operations continued through the night.

18.3 Criteria for Speech Communication

In many working spaces in factories and in offices, efficient performance of tasks is often dependent upon the ability of people to talk to each other. Whether the environment is a conference room or a machine shop, noise conditions should be adjusted to permit communication suited to the task that is to be performed. The type of communication desired may be of various kinds, from conversation in a normal voice at, say, 20 ft to shouting danger signals at a distance of 6 in from the listener's ear. The acceptable levels of the masking noise are dependent, therefore, upon the particular tasks involved and upon the degree to which speech communication is important in the performance of these tasks, or in the maintenance of adequate morale among employees (see Sec. 17.2).

In this section, criteria are suggested for noise levels that should be acceptable in spaces where speech communication is an important consideration. Account is taken of not only the level of the masking noise but also the vocabulary to be used in the communication, the voice level, the distance from the speaker to the listener,etc.

Two general types of basic material are available for substantiation of the proposed criteria for speech communication: (1) data have been presented in Sec. 16.4 on the physical properties of speech and on laboratory experiments concerned with the effects of masking noise and other distortions upon the intelligibility of speech. In the laboratory experiments, intelligibility is usually expressed in terms of the percentage of words or other test items recorded correctly during a test, i.e., the articulation score. (2) field data of a subjective nature have been collected in places where people are exposed to noise and where they are required to talk to each other. Measurements of noise levels were made, and people were asked how well they could understand each other.

In the final evaluation it is necessary to interpret the above two sets of findings with care, since important differences exist in the way they were obtained. Most of the intelligibility tests in the laboratory were conducted with earphones. In studies of the masking of speech by noise, the masking noise was usually mixed electrically with the speech signal. It has been demonstrated, however, that higher articulation scores are obtained when the phases of the noise or of the speech in the two ears are different than if both signals are in phase in the two ears 4/ (sec. 16.4). Hirsh 5/ has, furthermore, shown that there is an improvement in intelligibility when the noise and the speech sources are located at different points in a room, provided the subject can move his head freely. When listening to a person speaking in a noisy room, one is usually at liberty to turn one's head to face the talker so that the speech arrives at the two ears in phase. The source of the noise is usually different from that of the speech, however, and consequently the noise signal at the two ears is not in phase. An improvement in intelligibility should therefore be expected over that predicted from laboratory experiments for the same speech-to-noise ratio, in which, however, both speech and noise are in phase at the two ears.

An incidental observation that is often important in field studies is that the listener is usually able to observe the lips and other gestures of the speaker. Thus he probably is assisted by visual cues as well as auditory ones when he attempts to understand what is being said. No quantitative data are available at present on the relative importance of such visual cues, but it is reasonable to suppose that they do make a contribution. This is a problem that might be of importance in military situations when marginal communication is possible during daylight hours.

Let us begin by reviewing briefly the pertinent data from Sec. 16.4 that relates speech intelligibility to the level of the masking noise. We note that the important frequency range for speech is 200 to 6000 cps, and that frequencies above and below this range contribute little to intelligibility. In fact, Fig. 16.38 of Sec. 16.4 shows that 80 percent of this important frequency range* is covered by the octave bands of frequency 600-1200, 1200-2400 and 2400-4800 cps. That is, the frequency components of speech within these bands contribute 80 percent to the articulation index.

It has been shown that a single number which, within certain limits to be discussed below, describes the masking effectiveness of a noise is the speech interference level (SIL) 6,7,8/. The SIL is defined as the average, in decibels, of the sound pressure levels of the masking noise in the three octave bands of frequency 600-1200, 1200-2400 and 2400-4800 cps** The speech interference level is intended to provide, therefore, a measure of the extent to which noise interferes with the ability of people to converse.

If the SIL is to be used to compare the ability of people to communicate by voice in different types of noise in different situations, certain precautions must be observed. Ideally, the voice level of the talkers should be fixed, the same type of vocabulary should be used, and the relative

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* As discussed in Sec. 16.4, the frequency scale is distorted in such a fashion that equal distances along the scale represent equal contributions to articulation index.

** In a discussion of acoustic criteria on shipboard spaces, Strasberg 9/ has defined the speech interference level as the average, in decibels, of the sound pressure levels in the four octave bands of frequency 300-600, 600-1200, 1200-2400, and 2400-4800 cps. In most applications, the difference between the values of SIL based on the two different definitions is not great.

positions of talker and listener should be about the same. In addition, the spectrum of the masking noise should be reasonably smooth, and should not deviate markedly from the speech spectrum shown in Fig. 16.27.

The SIL becomes a rather inaccurate measure of the masking of speech by noise if the noise contains intense low-frequency components. Miller 10/ has shown* that if a low-frequency masking noise (below 600 cps) is sufficiently intense it can mask speech completely. For this case the SIL could be quite small; hence it would not constitute a valid measure of the amount of masking.

If the noise spectrum has a steep slope and is rather irregular in the range 600-4800 cps, the process of estimating the average noise level in each octave band and averaging the levels in decibels is likely to introduce some error. In the limiting case of the masking of speech by pure tones, square waves and pulses (Fig. 16.33) the use of the SIL to predict the amount of masking would clearly be subject to considerable error. For example, Stevens, Miller and Truscott 11/ show that a pure tone of frequency 500 cps is the most effective sine wave masker of speech. It would be meaningless to talk of an SIL for such a masking signal.

A final observation concerns the time character of the masking noise. The concept of the SIL was originally based on data derived from experiments with continuous masking noise. If the noise is irregular or interrupted in time, the intelligibility is affected in a way which the SIL does not predict (see Fig. 16.34). If the SIL for this type of noise were measured with conventional instruments, the result would obviously depend upon the dynamic characteristics of the meter.

At present, we do not have sufficient experimental data to delineate the limits of intensity, shape of spectrum and time character of the noise within which the application of the SIL is valid. It is fortunate, however, that the masking noises encountered in most practical situations have a reasonably smooth spectrum and a uniform time character. In such situations the SIL does provide a reasonably good approximation of the effectiveness of a noise in masking speech. The validity of the use of the SIL is also justified by many observations in the field, some of which are cited below.

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* Figs. 16.31 and 16.32 of Sec. 16.4.

Under the limitations discussed above we conclude that ability to communicate by voice in the presence of noise is determined essentially by four factors: (1) the SIL of the masking noise, (2) the voice level used by the talker, (3) the distance from the talker's mouth to the listener's ear, and (4) the nature of the vocabulary used in communication.

For example, a talker is better understood in the presence of noise if he raises his voice and moves closer to the listener. Also, we have shown in Sec. 16.4 that intelligibility is strongly dependent upon the nature of the vocabulary; the score is higher for digits than for unselected words, for example. Thus if the only words used in conversation were, in a linguistic sense, maximally distinct 12/, a much higher noise level could be tolerated than if continuous conversation were necessary.

Beranek 6,7/ has investigated the degree to which SIL, voice level and distance between talker and listener control the ability to carry on a reliable conversation. Table 18.5 summarizes his findings. If a prearranged restricted vocabulary were to be used, the distances between talker and listener could be increased. The amount of increase would depend upon the size of the vocabulary 13/, other things being equal. (See Sec. 16.4).

It is assumed that the talker has an average voice and the listener normal hearing. A normal voice level is the level one would use in a quiet office talking with a friend. A very loud voice level is the highest voice level one can maintain over a period of time without becoming hoarse. There are often pronounced differences in the voice level used by different talkers. A "normal" voice level may vary by as much as ± 8 decibels, depending upon the talker. Thus the numbers in Table 18.5 must be interpreted as statistical averages only, and should be applied with caution in situations involving only one or two individuals.

Empirical evidence indicates that there is a difference of about 6 db between the categories of voice level shown in Table 18.5 for the average talker. Thus the SIL's change in 6 db steps as we move across the table. The SIL's decrease with increasing distance, owing to the "inverse square" decrease in speech level with distance. It should be noted, however, that the sound pressure level at some distance from a source in a room may be greater than that predicted from the inverse square law, owing to reverberation in the room (Chapter 3).

TABLE 18.5 6,7/

SPEECH INTERFERENCE LEVELS (IN DECIBELS RE 0.0002 DYNE/CM^2) WHICH BARELY PERMIT RELIABLE CONVERSATION AT THE DISTANCES AND VOICE LEVELS INDICATED

Voice Level Distance (ft)	Normal	Raised	Very Loud	Shouting
0.5	71	77	83	89
1	65	71	77	83
2	59	65	71	77
3	55	61	67	73
4	53	59	65	71
5	51	57	63	69
6	49	55	61	67
12	43	49	55	61

This fact mav have to be taken into account when Table 18.5 is used. The Table applies to the case in which there are no reflecting surfaces nearby, and the listener and talker are facing each other.

Laboratory data on the intelligibility of speech masked by noise are in general agreement with the data of Table 18.5. For example, Miller 10/ has investigated the masking of speech by white noise, by bands of noise and by speech itself. If we comput the SIL's of his masking signals we find that in most cases the SIL's which barely permit reliable conversation (i.e., a sentence intelligibility close to 100 percent) agree with the levels of Table 18.5 within a few decibels. We must make allowance for the fact that Miller's subjects wore earphones, and that subjects who listen without earphones and are free to turn their heads would obtain somewhat higher articulation scores. In addition, we find general agreement between Beranek's 6,14/ graphical scheme for computing the articulation index and the data of Table 18.5, provided the spectrum of the masking noise does not differ markedly from the speech spectrum.

The original field studies 6/ that attempted to validate the SIL concept were carried out in the presence of "simulated airplane noise" (from propeller driven aircraft). In a later survey of noise in office spaces, Beranek and Newman 7,8/ were able from their measurements and questionnaires to validate in a general way some of the data in Table 18.5. Few other systematic studies have been conducted. However, numerous observations have been accumulated, and the "expert" can usually tell if the SIL concept will predict correctly or not. A comprehensive investigation relating ability to converse to octave band measurements of the interfering noise in various environments would prove most valuable.

The field studies have also provided information on the nature of the possible communication in various noise environments. For a SIL of 45 db, relaxed conversation was possible; for a SIL of 55 db, continuous communication was possible, but usually in a somewhat raised voice. Intermittent communication would be carried on in a noise with a SIL of 65 db, whereas only a minimal type of communication was possible at a SIL of 75 db. A restricted prearranged vocabulary might be desirable at a SIL of 75 db.

The above comments on the SIL, distance, and voice level necessary for reliable conversation amount to the assumption that the frequency components of a noise below 600 cps are not effective in masking the speech. The type of noise spectrum normally encountered in secretarial offices, tabulating rooms and private offices is well-behaved from the viewpoint of the SIL concept.

Laboratory data summarized in Figs. 16.31 and 16.32 of Sec. 16.4 have shown that low frequency noise of high level can be a very effective masker of speech. Under these circumstances, the masking effect of the noise is not limited to the frequency band in which there is noise energy, but extends into the higher frequency range. Thus for a masking noise which has intense low frequency components, the SIL is not an adequate measure of the masking effectiveness. If a given quality of speech communication is desired (the quality being defined in terms of voice level and distance required for reliable conversation, as in Table 18.5), we must specify the maximum acceptable levels of the masking noise in each octave band of frequency below 600 cps, as well as the SIL.

Such a specification is presented in Fig. 18.5 in the form of speech communication (SC) criterion curves. The extrapolation of these curves to low frequencies is based on empirical evidence. Further field data on masking of speech by low frequency noise are required to provide further validation of the low frequency portions of the curves. The SC-55 curve, for example, specifies for each octave band of the masking noise the sound pressure level that must not be exceeded if speech communication conditions comparable to those for a SIL of 55 db (from Table 18.5 are to be realized.

The speech communication criteria are summarized in Table 18.6. The number designating the SIL is shown in the left column. Other columns indicate the voice level, the distance from talker to listener, and the nature of the possible communication. The final column suggests the type of working spaces for which the various criteria are recommended. This table summarizes (1) data recorded by means of questionnaires administered during a survey of noise levels, (2) evaluative opinions with regard to noise in working spaces, and (3) experience of acoustical consultants at many different locations. A more detailed discussion of criteria for noise control in certain specific types of working areas is presented in Sec. 18.5.

Figure 18.5 shows curves SC-25 and SC-35, although a description of the communication conditions and environments for which these criteria are applicable is not contained in Table 18.6. The low levels defined by these curves are not usually necessary in relatively confined working spaces. However, if reasonably good hearing conditions for speech and music are to be provided in auditoria, the background noise levels must be quite low. For example, a SIL of about 25 db would be desirable in large auditoriums where excellent hearing conditions must be provided, and where a high degree of speech intelligibility is desired 15,16/ (see Sec. 18.5).

18.4 Criteria for Prevention of Hearing Loss

In Sec. 17.4 we have seen that prolonged exposure to noises having certain sound pressure levels and frequency characteristics can produce permanent shifts in man's auditory threshold. In surroundings in which noise may produce permanent hearing loss, it is important to reduce or control the noise that reaches the ears of persons who must remain in the noisy environment. In these situations, criteria for noise control are required. Such criteria should specify the

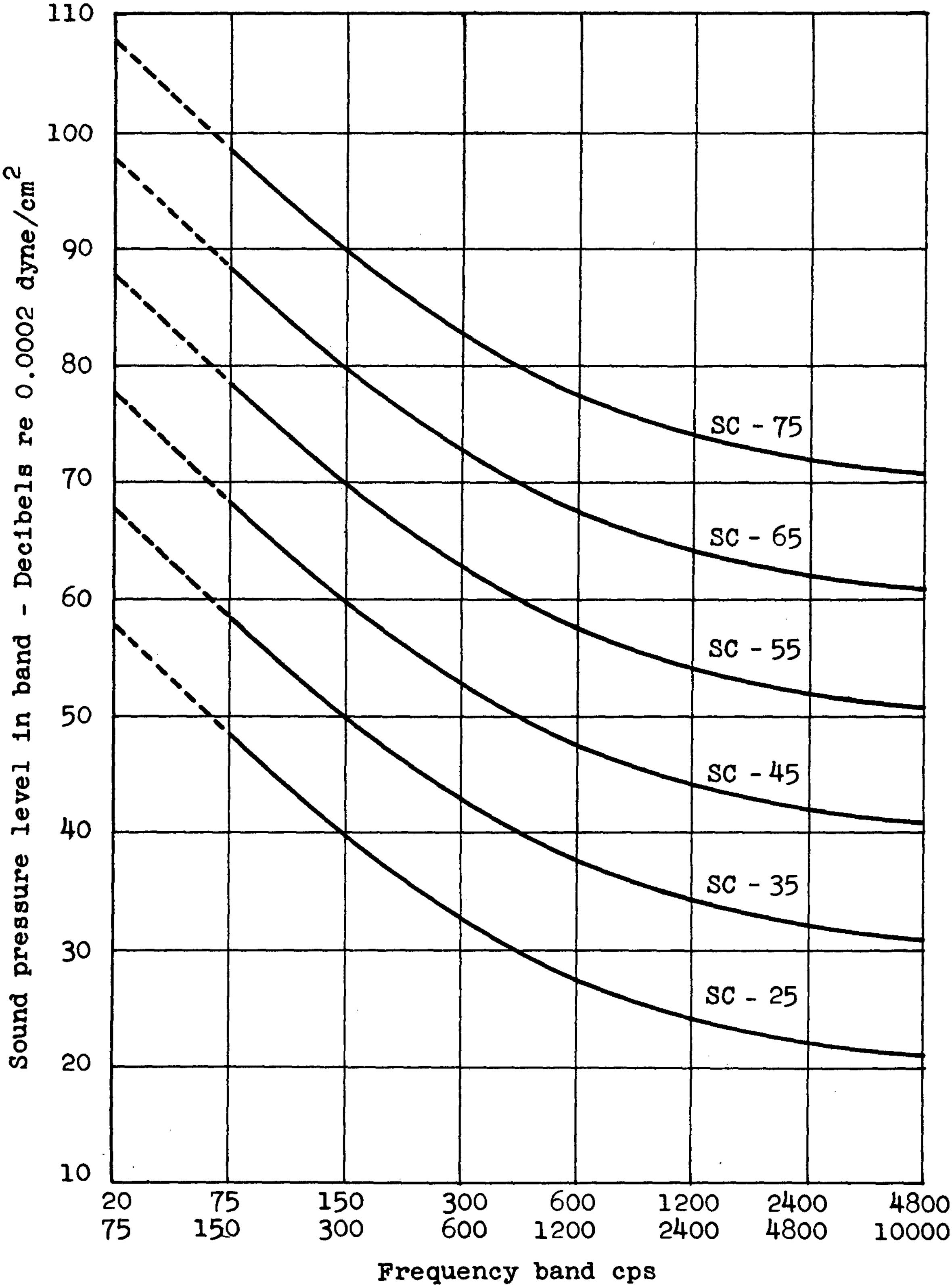
characteristics of noises that are unlikely to produce permanent hearing loss. A criterion of this type has been termed a Damage Risk (DR) Criterion. It is designed to reduce the risk that an individual will suffer permanent damage to his hearing. The concept of risk is a statistical concept; hence the successful validation of a DR criterion involves the demonstration that the incidence of hearing loss in the noise-exposed population does not differ significantly from the incidence in normal populations for the same age group.

The Specification of a DR Criterion. Before we begin to establish or even to propose a DR criterion, we must decide how such a criterion is to be specified. What are the important characteristics of the acoustic stimulus that are effective in producing permanent hearing loss? How is man's reaction to the exposure, i.e., the damage to his hearing, to be measured and specified? Some of these matters have been discussed in some detail in Sec. 17.4, so that we need to present here only an outline of the considerations that are pertinent to the specification of a DR criterion.

Let us first examine the aspects of the exposure stimulus that are likely to be important in producing permanent hearing loss. It is clear that the sound pressure level of the noise to which an individual is exposed is an important determinant of the damage that may be expected. Other things being equal, the more intense the noise the greater is the probability for the occurrence of permanent hearing loss. We could even think of defining a population threshold for permanent damage in terms of a convenient probability value, of, say, 50 percent.

Figure 18.5

Speech communication (SC) criteria. The curves are labeled with numbers equal to the speech interference levels they represent. Each curve specifies the octave-band pressure levels that must not be exceeded if a certain quality of speech communication is to be guaranteed. In each case the quality of speech communication is given in Tables 18.5 and 18.6 in terms of the SIL, voice level, distance from talker to listener, and type of vocabulary to be used.



110
100
90
80
70
60
50
40
30
20
10
Sound pressure level in band - Decibels re 0.0002 dyne/cm2
SC - 75
SC - 65
SC - 55
SC - 45
SC - 35
SC - 25
20 75
75 150
150 300
300 600
600 1200
1200 2400
2400 4800
4800 10000
Frequency band cps

TABLE 18.6*

SPEECH COMMUNICATION CRITERIA

Relation between SC Criteria Expressed by Speech Interference Levels and The Communication Conditions for a Degree of Intelligibility that is Marginal with Conventional Vocabulary and Good with Selected Vocabulary.

SIL in Decibels	Voice Level and Distance	Nature of Possible Communication	Type of Working Area
45	Normal Voice at 10 ft	Relaxed Conversation	Private Offices, Conference Rooms
55	Normal Voice at 3 ft	Continuous Communication in Work Areas	Business, Secretarial, Control Rooms of Test Cells, etc.
	Raised Voice at 6 ft		
	Very Loud Voice at 12 ft		
65	Raised Voice at 2 ft	Intermittent Communication	
	Very Loud Voice at 4 ft		
	Shouting at 8 ft		
75	Very Loud Voice at 1 ft	Minimal Communication (danger signals; restricted prearranged vocabulary desirable)	
	Shouting at 2 - 3 ft		

* Before this table is used, the comments and limitations noted in the text should be consulted.

In Sec. 17.4 we have seen that noise-induced hearing loss is not frequency independent. We should expect, therefore, that permanent damage to hearing depends upon the spectrum of the noise as well as its overall sound pressure level.

The temporal character of the exposure is another important variable. The evidence from laboratory and field data has shown that the amount of permanent hearing loss that is incurred is not independent of the duration of the exposure. There may even be a measurable effect of intermittency, i.e., of the way in which the exposure is packaged in time. Exposure to a certain noise every working day for a lifetime will produce after-effects that differ in order of magnitude from those incurred after a day, a week and perhaps even a year of exposure to this same noise.

The impulsive character of the noise is another important parameter of exposure. A noise that is characterized by sharp peaks (such as the noise in a drop forge shop) will not necessarily produce more damage than a continuous noise with an intensity that is appreciably lower than the peak intensity of the impulsive noise. In the discussion that follows, we shall be concerned chiefly with noises whose time character is relatively uniform. We shall, however, cite a case history in order to indicate how one might go about modifying the DR criterion for steady noise in order to extend its application to a noise of the more impulsive type.

Specification of <u>man's reaction or response</u> forces us to settle upon a method for determining the damage to man's hearing. Such a decision involves many complex problems. If we require that the exposure stimulus must not produce significant permanent damage to hearing, we must spell out (1) the exact way in which this damage is to be measured, and (2) the amount of permanent damage that we are willing to consider <u>significant</u>.

In Sec. 16.3 (Audiometry), we have seen that damage to hearing can be measured in several ways. We also tried to stress the fact that the different measures will not necessarily be highly correlated. We can, for instance, determine the hearing loss for pure tones at each of several frequencies. Alternately, we might be concerned with hearing loss for speech or with discrimination loss. We have seen that in some respects the use of speech material as test stimuli provides the most meaningful measure of the social adequacy of man's auditory capacity.

Various formulae have been suggested (Fowler 17/, American Medical Association 18/, Carter 19,20/, and Fletcher 21,22/) in order to arrive at a single overall figure for a person's hearing loss. These formulae weight the several test frequencies differently. Their authors differ also in the way in which they combine losses for the two ears. Currently new attempts are under way to write medico-legal standards for compensation resulting from injury. Both pure tone audiograms and data on speech intelligibility will be considered. However, for the present, we shall base our criteria upon permanent threshold shifts for pure tones*.

Several complications attend the specification of the amount of hearing loss for pure tones that we shall agree to consider "significant". In Sec. 16.3 we referred to the various "normal" audiograms established by several hearing surveys. We also noted the phenomenon of presbycousis, i.e., the increasing hearing loss, especially for the higher frequencies, with age. We further noted that for the older age groups hearing losses for the higher frequencies are by no means "normally" distributed (in a statistical sense). There is a strong tendency for the distribution curves to be skewed toward the high loss end. It follows that an audiogram exhibiting perceptive hearing loss for one individual cannot give positive information on whether his hearing loss is due to exposure to noise or to other factors such as infections, tumors, or old age. Since there is a substantial variation in hearing loss among the population, specification of the amount of hearing loss that is to be considered significant must be in statistical terms.

One standard technique of demonstrating statistical significance of the incidence of hearing loss in an industrial population for instance, would consist in showing that its mean hearing loss is different than the mean hearing loss of a standard (or control) population at a level that is statistically significant. Such a procedure is eminently desirable but is rarely attainable in view of the sampling problems involved. In practice we may have to be satisfied with tests that are statistically less satisfactory. For example, we might hope to show that the audiograms of an experimental population (i.e., of a population that has been exposed) do

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* We emphasize that these criteria are aimed at perceptive (or nerve) deafness only; conductive losses are clearly unrelated to after-effects of exposure to noise.

or do not differ significantly from their audiograms measured before exposure. On the other hand we might, in the absence of exposure data, have to be satisfied with a finding that indicates an abnormally high percentage of people in the exposed population whose audiograms exhibit hearing losses in the higher frequencies of the order of 20 or 25 db (or even higher). Such losses would place the individuals concerned into the category of the 5 or 10 percent of the American population who hear most poorly.

The comments presented above indicate that an adequate specification of a DR criterion is a complicated matter involving many variables. The kind of criteria we should like to set up should be based upon thorough, long-term studies involving data of the type discussed above. At present we do not have such data, but we are in a situation where it is considered necessary to set up tentative criteria for immediate use. We should, incidentally, be sure that our tentative criteria can provide a reasonable framework for future validating studies*.

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* The above comments should also make the lack of agreement among certain criterion-makers more plausible. It is really so surprising that, in the absence of agreement on definitions of exposure and hearing loss, Sterner's poll 23/ of more than 200 acousticians, otologists, psychologists, industrial physicians and hygienists indicated wide differences of opinion on the question of a DR criterion? Even if these men had come to a preliminary agreement on definitions, they would still have been faced with a lack of data. Whatever data exists hardly satisfies the necessarily multidimensional requirements of such definitions. Only recently have the various professions become aware of the necessity of gathering the appropriate data. Since the taking of such data can not be rushed, it will probably take a few years before we will have the evidence upon which to base more than a tentative DR criterion.

Since World War II the problems of noise have claimed the attention of many groups. Conferences organized by the medical profession 24/, the Noise Abatement Symposia 25/, and the University of Michigan Training Course 26/ testify to the popularity of the subject. However, the group that has done the most persistent job of drawing the attention of responsible management officials, industrial physicians and hygienists, and safety engineers to the problems of

A Proposed DR Criterion for Steady Noise and Lifetime Exposures. The starting point for our suggested criterion is Kryter's monograph 2/. In a discussion of Maximum Safe Intensity Level we find the following statements: "A fair, perhaps conservative evaluation of the laboratory and industrial studies on stimulation deafness would seem to be that for long and intermittent exposures any frequency of sound (or narrow band not exceeding the critical width) that is 85 db or less above 0.0002 dyne/cm^2 will not cause any temporary or permanent deafness. The "guess" that tones 85 db above 0.0002 dyne/cm^2 may cause some deafness, either temporary or permanent, applies only for long periods of exposure, applied intermittently over months or years. On the other hand, for brief exposures lasting up to an hour, the intensities necessary to cause deafness appear to be in the order of 100 db re 0.0002 dyne/cm^2 for any frequency or critical band." Somewhat further on in his monograph Kryter states: "It is possible, but undemonstrable with present data, that the degree of deafness could be predicted by the use of critical band measures of noise intensity and plotting such measures relative to 85 db above the threshold for pure tones in a manner somewhat similar to that ... [used] for calculating speech intelligibility. A suitable threshold line would be the minimum audible

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* noise-induced hearing loss is the so-called Subcommittee on Noise in Industry. (Its parent committee is the Committee on Conservation of Hearing of the American Academy of Ophthalmology and Otolaryngology). The subcommittee has a field office in the Los Angeles area; it has conducted surveys of industrial noise and deafness; it has been concerned with problems of ear protection and has worked on the design of so-called predictive tests (tests capable of predicting on the basis of a short exposure to a carefully controlled noise how a given individual might react to prolonged exposure to industrial or airplane noise, for instance). Recently the American Standards Association has set up a subcommittee under the name of "Bio- and Psycho-Acoustic Criteria for Noise Control" (Z 24-X 2). Its first task is to explore whether the data available would permit the writing of tentative standards, i.e., criteria in the area of noise-induced hearing loss. Finally, mention should be made of the Committee on Noise of the Acoustical Society of America. The committee attempts to act as a clearing house for the almost one hundred groups that are in various ways concerned with the effects of noise on man.

pressure [curve] ... Because of the greater intensities required to reach thresholds at low and high frequencies, 0.0002 dyne/cm^2 would represent a more conservative, safer reference point for calculating the probable deafening effects of noise than the minimum audible threshold; further experiments are needed to determine which reference level is more suitable." We have quoted these excerpts in their entirety since the Kryter criterion has been incorporated into several other criteria and since it has also been misunderstood by some.

As justification for his proposed criterion, Kryter refers to several laboratory experiments on the temporary effects of exposure to high intensity stimuli and to several field studies of hearing loss following exposure of workers to industrial noise. Since sufficiently detailed and extensive data were not available, Kryter was unable to specify the criterion in more detail.

Since our DR criteria are designed to prevent permanent damage we have to exclude consideration of temporary deafness. We have seen in Sec. 17.4 that practically all audible stimuli give rise to temporary threshold shifts. Some of these phenomena last a few milliseconds only; in others, recovery extends over periods of several hours, days and perhaps even months. We shall be concerned here with permanent shifts only, i.e., shifts that represent irreversible changes in the organism's response capacity after a reasonable recovery interval has intervened between the end of exposure and the audiogram showing the loss.

Next, we should like to aim for a more precise statement of the characteristics of the exposure both with respect to duration and spectrum. Finally, we feel that there is some necessity for introducing a statement about the way in which such a criterion can be calibrated with respect to hearing loss. In other words, we need to specify in a statistical way the amount of hearing loss that we shall consider to be significant.

It is from this viewpoint that we have modified and qualified the so-called Kryter criterion. Our definition of hearing loss is the one developed in the first part of this section, with major emphasis upon the type of high frequency hearing loss that is potentially a forerunner of more serious trouble in terms of impaired speech communication.

Kryter hesitated between two contours, one at 85 db re 0.0002 dyne/cm^2 and the other at 85 db sensation level (presumably above the binaural MAF threshold). In the light of the available evidence we took a compromise position between the two contours. We did not feel that we could go as high as 85 db sensation level at the low frequency end, this would have meant approximately 125 and 140 db SPL in the frequency bands 75-100 and 20-75 cps respectively. However, evidence on exposure to low frequency noise (such as that obtained in the cabins of conventional aircraft) seems to indicate that noises in which the energy is concentrated below 300 cps are less effective in producing permanent hearing loss than stimuli of equal SPL in the middle range of frequencies around, say, 1200 cps. Hence the upward bend in our criterion curve for frequencies below 500 cps, as we shall see in Fig. 18.6.

At high frequencies there is a range in which the 85 db sensation level contour represents the more conservative position than the 85 db SPL contour. In this region the binaural MAF threshold falls below 0 db SPL because of diffraction effects around the head and resonances in the outer ear. We have again made a compromise on the conservative side. Without dropping as low as 85 db sensation level, we have taken some account of the evidence that seems to indicate particular sensitivity to hearing loss in this frequency region. Thus our criterion in the region between 1200 and 4800 cps slopes slightly below 85 db SPL. Little importance should be attached to the frequency region above 4800 cps in view of the difficulties of measuring thresholds of audibility for such frequencies and the relatively small importance of these frequencies in the communicative process.

Our discussion of frequency characteristics has applied to pure tones or to stimuli for which a major portion of the energy is concentrated in bands that are narrower than the critical width (see Sec. 16.2). In order to specify a criterion for wide band noise, we must make an assumption regarding the way in which the effects of exposure stimuli at different frequencies combine. Kryter's criterion stated that the level of the noise must not exceed certain specified levels

(85 db SPL modified as indicated above) in <u>any</u> critical band*. The implication is that critical bands contribute independently to hearing loss. Unfortunately this assumption cannot be justified on the basis of present laboratory and field data (see discussion in Sec. 17.4). As a matter of fact the few data collected by Davis and others during World War II (for levels around 125 db SPL) showed octave bands of noise and pure tones within the octave to be equally effective in producing hearing loss, provided they had the same SPL.

Since most of our measuring instruments read octave-band levels, we must translate our critical band specifications into octave band specifications. Thus if the criterion specifies 85 db SPL in a critical band Δf_c, it should specify

$$85 + 10 \log \frac{\Delta f_o}{\Delta f_c} \text{ db}$$

in an octave band Δf_o, if we maintain our assumption of the independent contribution of critical bands to hearing loss. The width of the critical band as a function of frequency has already been shown in Fig. 16.19.

Finally we come to the problem of the duration of the exposure. The contours that we suggest are intended to represent safe levels in terms of exposure in a lifetime of work. At this stage we are hesitant to modify the criterion levels toward higher values for exposures that are less severe, but that still last over a period of months. For very short exposures, however, we shall indicate that higher levels can be tolerated.

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* Kryter's comments on the question of critical bands are as follows: "It has been assumed by Fletcher and others that the concept of critical band (the narrowest band around any frequency which just masks that frequency when of equal over-all intensity) should cover not only masking phenomena but also the deafening effect of noise. The assumption is that since the addition of sound frequencies beyond the critical bands does not contribute to the masking effectiveness of the noise within the critical band, these additional frequencies likewise contribute nothing to the deafening effect of the noise within the critical band".

In summary, we show in Fig. 18.6 the SPL contours for octave bands and for critical bands that define our DR criterion. The following qualifications should be applied when this DR criterion is used:

1. These contours are not to be taken too literally since deviations of the order of 1 or 2 db in either direction could probably be disregarded. Contours such as these should be interpreted as zones with some uncertainty attending the measurement of the exposure stimulus, and biological variability modifying the probability of damage. We feel, however, that contours 10 db lower would involve negligible risks indeed, while contours 10 db higher would result in significant increases in hearing loss.

2. The levels are considered to be safe in terms of exposures during working days for durations up to a lifetime.

3. The criterion levels apply to exposure noise that has a reasonably continuous time character with no substantial sharp energy peaks.

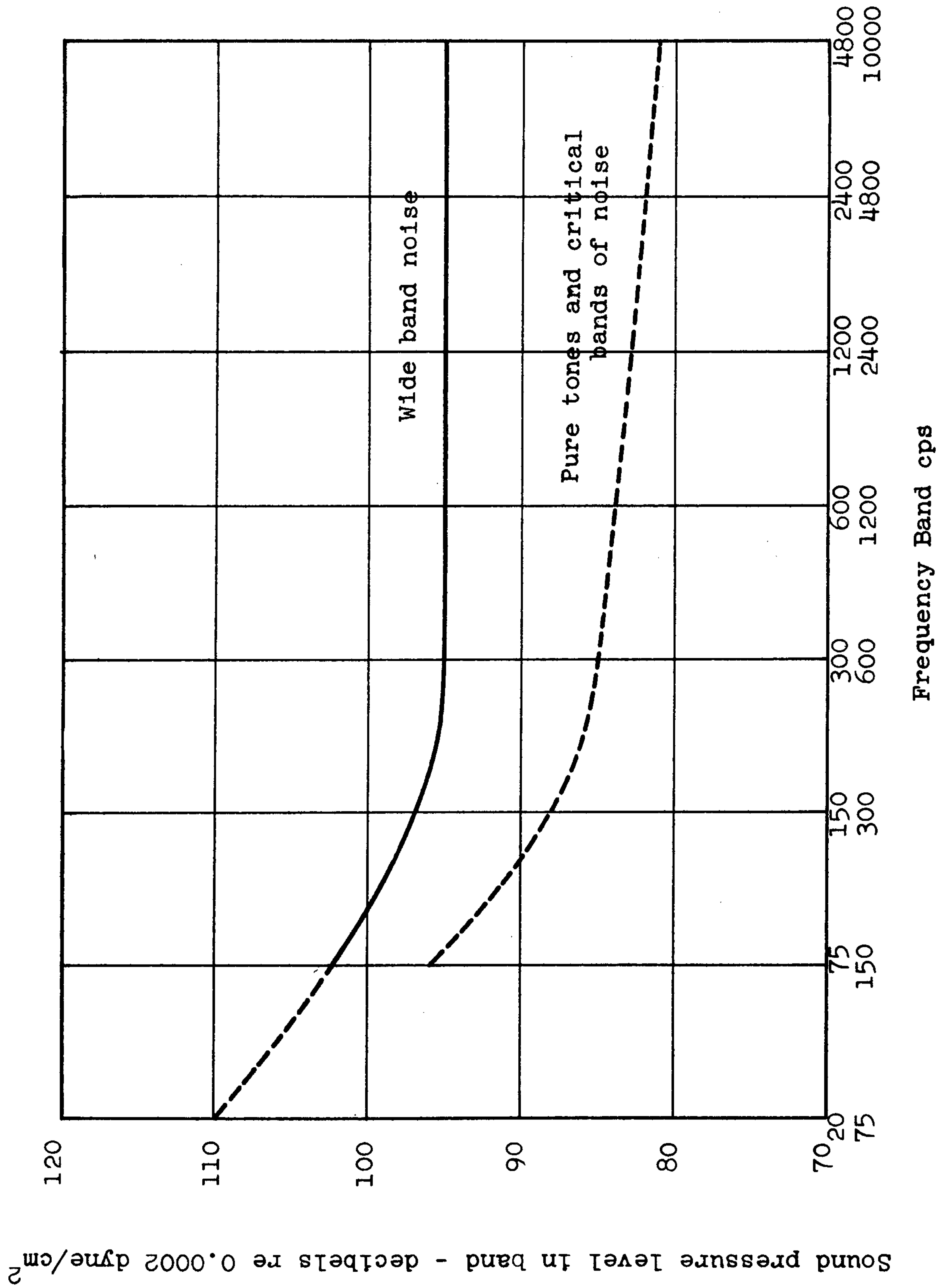
4. For wide-band noise, the curve designated "octave bands" should be used. For pure tones or for noise in which the major portion of the energy is concentrated in a band narrower than the critical band, the curve designated "critical bands" should be used. In the latter case, the abscissa should be interpreted as a logarithmic frequency scale rather than a scale of octave bands of frequency.

5. The criterion should be considered as tentative only, and is subject to further revision as new laboratory and field data are reported.

Criteria for Short Exposures. For short and very intermittent exposures of the order of minutes in duration, higher levels than those shown in Fig. 18.6 may be tolerated.

Figure 18.6

Damage risk (DR) criterion for steady noise and for lifetime exposures. The upper curve applies to situations in which the noise is wide-band; the lower curve applies to pure tones or to bands of noise of critical width or less. For an interpretation of these curves, including their statistical character, see text.


Sound pressure level in band - decibels re 0.0002 dyne/cm²
120
110
100
90
80
70
Frequency Band cps
20 75
75 150
150 300
300 600
600 1200
1200 2400
2400 4800
4800 10000
Wide band noise
Pure tones and critical bands of noise

There is some evidence from animal experimentation that there is an upper limit in the neighborhood of 150 db 27/. Stimuli of that intensity seems (at least in anesthetized guinea pigs) to produce irreversible damage at the end of time intervals of the order of one minute. There are isolated cases in which individuals have been exposed to reliably measured levels higher than 150 db SPL. The effects (see Sec. 17.4) have been of a "prolonged temporary" nature, and might have produced irreparable damage in other individuals. We recommend, therefore, that even for rather short exposures of the order of one minute or so, levels of 145 db to 150 db should not be exceeded. No person without well-fitting ear protection should really be exposed to levels higher than 140 db for any appreciable length of time. At such high intensities, the overall level of the noise is probably the best measure of the exposure stimulus, since the effects seem to be more or less independent of frequency. Let us also not forget that at levels in the vicinity of 150 db SPL we may have to supplement our criteria designed to prevent damage to hearing by criteria based on performance of the organism in the non-auditory sphere.

Example of a DR Criterion for Impulsive Noise. We present here an example of a DR criterion for noise that is not continuous in time but is of an impulsive character. The criterion was proposed specifically for the protection of operators in a drop forge shop from the noise of their drop hammers. It is presented here to indicate some of the factors that must be considered when we try to modify the DR criterion for steady noise and apply it to impulsive noise.

The physical characteristics of the sound from a drop forge have been described in Sec. 7.4, Figs. 7.10, 7.11 and 7.12. The stimulus is characterized by large peaks of energy of a few milliseconds duration. The sound from any one drop forge in this particular case is repeated at a rate not exceeding one per second. Thus the average SPL from a drop forge is much lower (about 20 db) than the peak SPL. It is difficult, therefore, to obtain numbers that adequately describe the noise in a simple fashion.

Information on temporary and permanent effects of exposure to short tones and noises has been reported in the literature (see Sec. 17.4) and a reasonable estimate of a suitable damage risk criterion can be made on the basis of these data. Certain relevant data are summarized in the following paragraphs.

Relatively brief exposures of a few hundred milliseconds to tones at levels considerably below the level of the DR criterion for steady sounds are followed by temporary upward shifts of the threshold of hearing for tones of the exposure frequency and of neighboring frequencies. The magnitude and duration of this temporary shift or "fatigue*" increases as the intensity of the exposure time is increased. When the level of the exposure tone becomes greater than a critical value in the range 90-100 db, the increase in fatigue becomes quite sharp. Further data show that the short-time auditory fatigue is independent of the duration of exposure for sounds of low intensity level, over a range from 1/10 second to 10 seconds. As the level of the exposure time is raised to about 80 or 90 db, however, the induced hearing loss increases with increased duration of exposure. Unfortunately, the levels investigated did not, in general, exceed the range 90-100 db for the middle and high frequencies.

These data on short-time auditory fatigue indicate that a drop forge operator must undergo considerable temporary hearing loss after each hammer impact. The temporary loss rapidly decreases within one or two seconds. However, the temporary loss may not decrease to zero before another hammer impact occurs.

There is also evidence to show that short exposures (up to, say, several hours continuously) to sounds like the impact sounds from the drop hammers give rise to temporary hearing losses that persist for a few hours or days. Typical examples of the effects of intermittent noise are hearing losses reported in habitual hunters and in gunnery instructors.

As noted above in the discussion of criteria for short exposures, there is apparently an upper limit of intensity capable of producing damage to the hearing mechanism no matter how short the duration of the physical exposure. From the small amount of evidence available at present 27,28/, this limit will be placed tentatively between 150 and 160 db sound pressure level re 0.0002 dyne/cm^2. The peak levels from the drop hammers considered here are always less than 150 db at the operator's ear position, and consequently we shall assume that there is no permanent damage from only a single impact sound.

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* See Sec. 17.4

The damage risk criterion previously determined for steady noise will be used as a basis for the establishment of upper and lower limits of peak sound pressure level, between which the damage risk criterion for impact noise must lie.

The criterion for steady noise places an upper limit of about 95 db on the sound pressure level in each octave band between 300 and 10,000 cps, to insure reasonable freedom from damage. Impact sounds whose peak sound pressure levels do not exceed 95 db in these octave bands are therefore assumed to cause no permanent damage to hearing, even when they are repeated many times.

An upper limit beyond which there is a definite risk of damage may be determined as follows. The average sound intensity (and hence the average sound intensity level) to which the operator is exposed is computed for each octave band, assuming fluctuations in sound pressure similar to those depicted in Fig. 7.12. If the levels determined in this manner are greater than the DR criterion level for steady noise, there is definite risk of damage. For the type of drop hammers considered here, an average SPL of 95 db would correspond to a peak SPL of about 115 db, in the octave bands above 300 cps.

It is almost certain that the best criterion lies between the two criteria discussed above. That is, a criterion specifying maximum peak levels of 95 db per octave band above 300 cps would be too stringent, whereas average octave band levels of 95 db would not afford sufficient protection.

Using known experimental data on short-time auditory fatigue 29/, a rough extrapolated estimate can be made of the amount of cumulative hearing loss induced by tone bursts repeated at a rate of one per second, and having a level of about 105 db. The data indicate that the effect of the first sound would have practically worn off by the time the second one is delivered. One must be very careful when one is trying to make such extrapolations, since it is by no means certain that the organism behaves like mechanisms that obey the superposition principle for repeated exposures. However, we may at least conclude that the order of magnitude of our suggested criterion is approximately correct.

Our tentative criterion for impulsive sounds having the character (i.e. time-characteristics, spectra, etc.) of those encountered in the drop forge shop can then be

formulated as follows: the peak sound pressure level within an octave band must be no more than 105 db, for the range from 300 cps to 10,000 cps. This criterion yields an overall peak sound pressure level of about 112 db for the average drop forge spectrum.

18.5 Miscellaneous Noise Criteria for Various Environments

The criteria for noise control that we have discussed in the previous three sections have been based on certain specified types of behavior on the part of the individual or individuals who are exposed to the noise. The three types of behavior are: (1) interference with residential living, (2) interference with speech communication, and (3) loss or partial loss of auditory function as a result of exposure to high intensity noise. Occasionally the type of behavior that is involved may not be covered by these three categories, or may include more than one category. Several such situations are discussed in this section.

Office Spaces. Noise in office spaces may interfere with several types of activity. It influences the ability of the occupants to talk to each other either directly or on the telephone; it may be responsible for or associated with fatigue, annoyance and irritability. It may indirectly (via speech communication, for example) affect the efficiency of the workers. Thus noise in office spaces does not only influence behavior but does so in a rather complex fashion.

In an effort to evaluate the noise levels that are acceptable to people in office spaces, Beranek and Newman 7/ made a survey in three large organizations: a metal producing company, a radio equipment factory, and an educational institution. They made physical measurements of the noise, and also measured people's reactions by means of a questionnaire. The questionnaire included the following questions:

(a) Rate the noisiness of this room by placing an "x" along the scale below:

/	/	/	/	/	/
very quiet	quiet	moderately noisy	noisy	very noisy	intolerably loud

(b) Rate your ability to use the telephone under the condition of noisiness for (a) by placing an "x" along the scale below:

satisfactory	slightly difficult	difficult	impossible

(c) On the same scale as for (a) check the noise rating that you feel should not be exceeded if you are to accomplish your duties without loss of performance.

(d) At what maximum distance in feet should you be able to converse with another person in your room in order that you may do your duties without loss of performance?

(e) In order that your performance not be affected, do you consider that at the distance indicated in the previous question you should be able to talk in a:

normal (quiet) voice	slightly raised voice	loud voice

At all pertinent locations in the office spaces, the sound pressure levels in octave bands of frequency were measured, and the speech interference levels were computed. Since interference with speech was believed to be the most important effect of the noise, it was concluded that the SIL would provide a meaningful single number that described the noise environment.

The average answers to questions (a) and (b) are shown in Fig. 18.7 as two curves. These curves are based on answers to 100 questionnaires. As the curves indicate, the office spaces were divided into two categories: (1) private offices,

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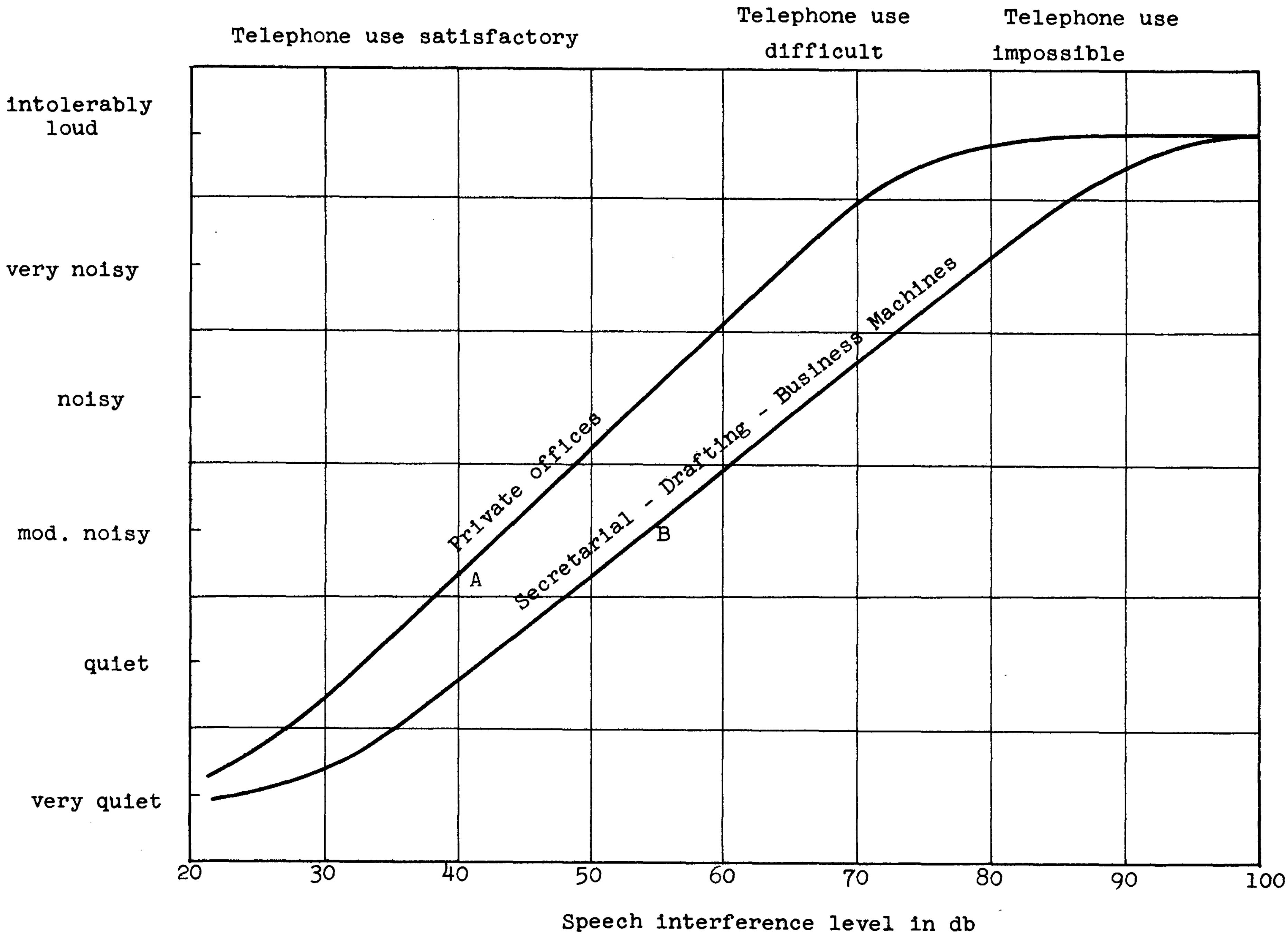
Figure 18.7

Subjective rating of noises in offices. The curves summarize in graphical form the results of 100 questionnaires issued during a survey of noise in office spaces. See text. (After Beranek and Newman 7/).


Telephone use satisfactory
Telephone use difficult
Telephone use impossible
intolerably loud
very noisy
noisy
mod. noisy
quiet
very quiet
Subjective rating
Private offices
A
Secretarial - Drafting - Business Machines
B
20
30
40
50
60
70
80
90
100
Speech interference level in db

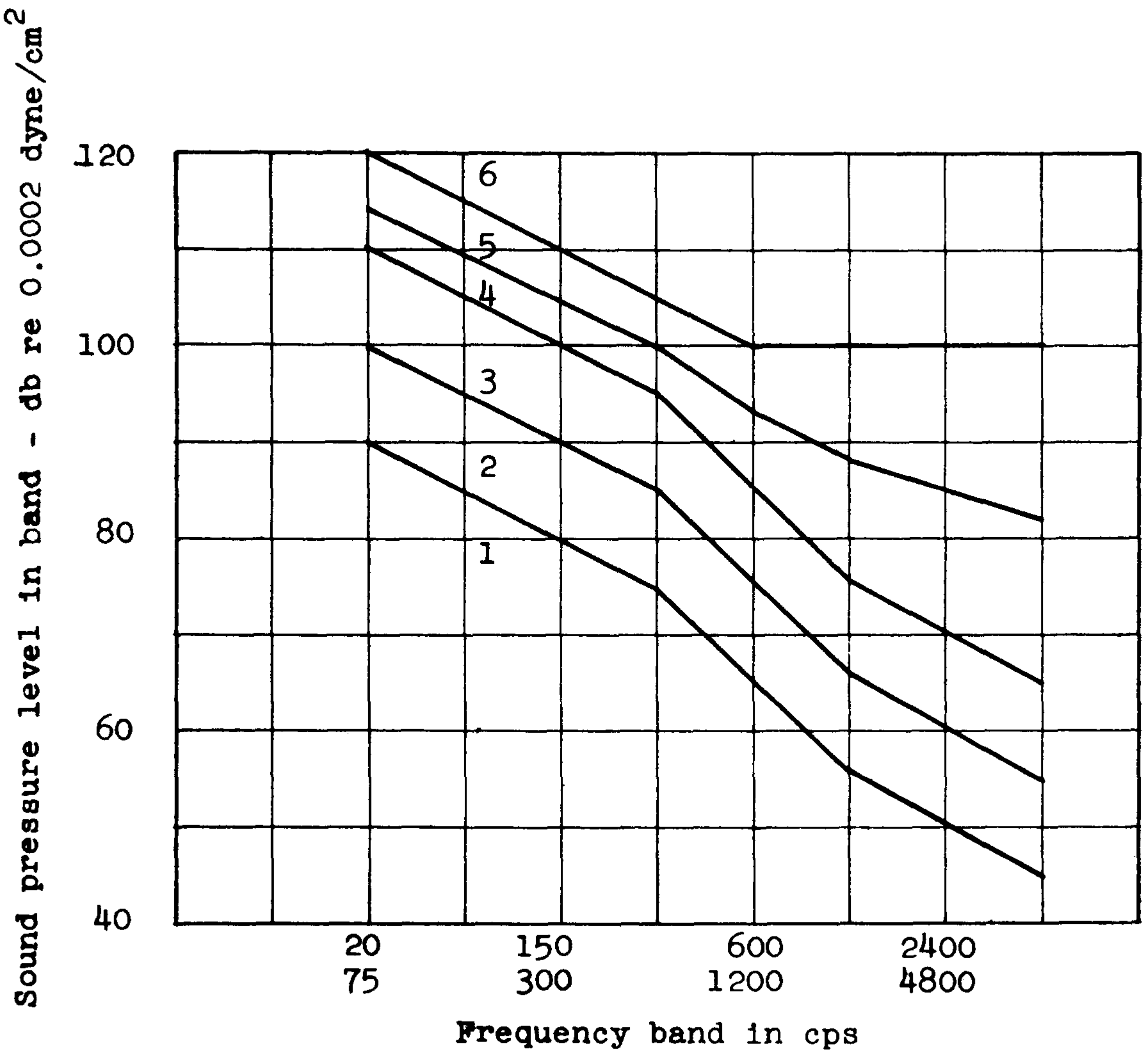


Figure 18.8

Graphical relation between judgment of comfort inside the cabins of commercial transport aircraft and the octave-band pressure levels. The six regions between the curves are defined as follows: (1) ideally quiet, (2) comfortable, (3) quasi-comfortable, (4) uncomfortable, (5) very uncomfortable, (6) intolerable. (After Lippert and Miller 17/).

and (2) secretarial and drafting offices and rooms with business machines. The average answers to question (c) are shown as points A and B on the two curves of Fig. 18.7. The average answer to (d) and (e) for private offices was "normal voice at 9 feet," and the answer for secretarial offices was "slightly raised voice at 3 feet."

The SIL's of 40 db for private offices and 55 db for secretarial offices can be used, therefore, as approximate criteria for noise control in these spaces (see Table 18.7).

Cabins in Commercial Aircraft. Lippert and Miller 30/ have studied the problem of acceptable noise levels inside commercial transport aircraft with reciprocating engines. From their experience, they indicate ranges of octave band levels that would be classified as (1) ideally quiet, (2) comfortable, (3) quasi-comfortable, (4) uncomfortable, (5) very uncomfortable and (6) intolerable*. Unfortunately no evidence is supplied that would permit us to estimate to what extent a representative sample of passengers would agree with these judgments. Their classification is shown graphically in Fig. 18.8. Curve A is considered as defining the upper limit of comfort for an airplane noise spectrum. It is of interest to note that a noise defined by Curve A would have a SIL of 77 db, and would, according to Table 18.5, permit conversation in a very loud voice at one foot. The region defined as "comfortable" would, by the same token, define an environment in which conversation is possible in a raised voice at three feet.

Typical Criteria for Other Spaces. Typical criteria for other spaces have been suggested 15/ in terms of the maximum permissible SIL measured when the room is not in use.

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* One should remember, however, that there is always a certain amount of vibration in aircraft, and that man's reaction, especially at higher levels, may be a composite of his reaction to noise and to vibration. Had the authors described in more detail the method by which their classification scheme was obtained it would be easier to evaluate the contribution that vibration makes to the concept of the "Acoustical Comfort Index."

These criteria are given in Table 18.8. As noted in Sec. 18.3, specification of the SIL alone does not define the permissible levels at low frequencies. In the absence of empirical validation, it is suggested that the maximum permissible levels at low frequencies be those defined by the curves in Fig. 18.5.

Although the criteria in Table 18.8 are specified in terms of maximum permissible SIL, it is reasonably clear that speech communication is not the only human function that is affected by the noise. Questions of sleep, comfort and annoyance are also involved to a degree that cannot easily be quantified at present.

TABLE 18.8

CRITERIA FOR CONTROL OF BACKGROUND NOISE IN VARIOUS SPACES

Type of Room	Maximum Permissible SIL (measured when room is not in use)
Small private office	40
Conference room for 20	30
Conference room for 50	25
Movie theatre	30
Theatres for drama (500 seats, no amplification)	25
Coliseum for sports only (amplification)	50
Concert halls (no amplification)	20
Secretarial offices (typing)	55
Homes (sleeping areas)	25
Assembly halls (no amplification)	25
School rooms	25

On the other hand, Knudsen and Harris 16/ have suggested in the following table recommended noise levels for unoccupied rooms.

TABLE 18.9 16/

RECOMMENDED ACCEPTABLE AVERAGE NOISE LEVELS IN UNOCCUPIED ROOMS

Type of Space	Sound Level* decibels
Radio, recording and television studios	25-30
Music rooms	30-35
Legitimate theatres	30-35
Hospitals	35-40
Motion picture theatres, auditoriums	35-40
Churches	35-40
Apartments, hotels, homes	35-45
Classrooms, lecture rooms	35-40
Conference rooms, small offices	40-45
Court rooms	40-45
Private offices	40-45
Libraries	40-45
Large public offices, banks, stores, etc.	45-55
Restaurants	50-55

* The levels given in this table are "weighted"; that is, they are the levels measured with a standard sound-level incorporating a 40-db frequency-weighting network 15/.

Vibration. At the present time, the literature contains little beyond laboratory studies in the area of acceptable levels of mechanical vibration 31,32/. As high sound fields produced by jet engines with afterburners become more prevalent, it can be safely predicted that empirical studies will be undertaken that will lead to the establishment of at least approximate criteria.

Present evidence indicates that the presence of vibratory phenomena in connection with the passing of aircraft (rattling of windows and dishes) increases the probability of complaints in residential areas. As better data on such incidents becomes available, it might prove necessary to take account of vibratory phenomena in the computation of the composite noise rating. (See Sec. 18.2).

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APPENDIX 1

The Ear: A Little Anatomy and Some Facts about the Auditory Nervous System

Some of you may have wondered why we have not started the discussion of hearing by giving a description of the structures of the ear and of the organization of the auditory system. The ability of a listener to distinguish various frequencies has often been explained by assuming the presence of resonators in the inner ear and you may have heard of the battle between the resonance theorists (Helmholtz 1/) and the so-called telephone theorists (Rutherford 2/).

This handbook is obviously not the place to compare critically the merits of various theories of hearing*. It might, however, be quite appropriate to discuss the ear's anatomy (or at least certain of its anatomical features). We might also want to review the numerous papers dealing with the electrical signals from the auditory nervous system, provided such discussions are capable of throwing some light upon the effects of noise on man. However, unfortunately there are only a few facts that have a direct bearing upon our problems at hand. We shall, therefore, limit our discussion in this appendix to a general outline of certain anatomical and physiological facts with emphasis upon those considerations that are relevant to a discussion of the effects of noise.

The human ear (see Fig. A1.1) is commonly described as consisting of three main parts: the outer ear (includes everything up to the eardrum), the air-filled middle ear cavity which contains the three ossicles, and finally the inner ear

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* Actually most of these theories are directed toward the phenomena of pitch perception, with minor emphasis placed on such aspects of auditory behavior as loudness and masking. No serious overall attempt has been made to develop a comprehensive theory ranging from speech perception to the after-effects of various sounds. It is undoubtedly premature for such an undertaking, but as the interaction between man and noise becomes more important it is to be expected that theorists will want to turn their attention toward these neglected aspects of man's responses to sounds.

consisting essentially of the cochlea and the vestibular apparatus. The vestibular apparatus is that part of the anatomy that is involved mainly in maintaining equilibrium. Let us now see how these parts of the ear's anatomy influence the behavior of an individual in his responses to sound.

The outer ear makes its influence felt when auditory thresholds are measured. The length of the ear canal up to the eardrum is approximately one inch long. This corresponds roughly to a quarter wavelength in air for a 3000 cps sound. This tuning accounts for a significant part of the difference between minimum audible field data and minimum audible pressure data in the frequency region around 3000 cps (see Sec. 16.2). Otherwise, the ear channel exhibits in its anatomical details great variability from man to man. This is a fact which we must keep in mind when we consider the wearing of ear plugs in order to keep unwanted sound from reaching the middle and inner ear.

The role of the three ossicles, named hammer (malleus), anvil (incus), and stirrup (stapes), is a fairly intricate one. There is some evidence that these three smallest bones in the human body act as an impedance transformer matching the acoustic impedance of air to the impedance of the fluid in the inner ear. Bekesy 5/ has established that these ossicles have at least two stable modes in which they can vibrate, as shown in Fig. A1.2. The transition from one mode to the other occurs for certain displacement amplitudes which exceed a certain critical value*. For high-intensity, low-frequency sounds an increase in stimulus intensity is accompanied by a decrease in the reported loudness. There is also some evidence that the pain or prickling sensation reported by observers in the presence of very intense sounds may be related to a rubbing of one of the ossicles against the tissues that cover the inside of the middle ear cavity. The middle ear acts further as a protective device: there are two small muscles in the middle ear, the stapedius muscle and the tensor tympani. While their action is not entirely understood, it is reasonably certain that their contraction reduces the transmission of low frequency sounds but has

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* Under this circumstance, the amplitude of oscillation transmitted to the inner ear is less than the amplitude that would be otherwise transmitted if the ossicles continued to vibrate in their principal mode.

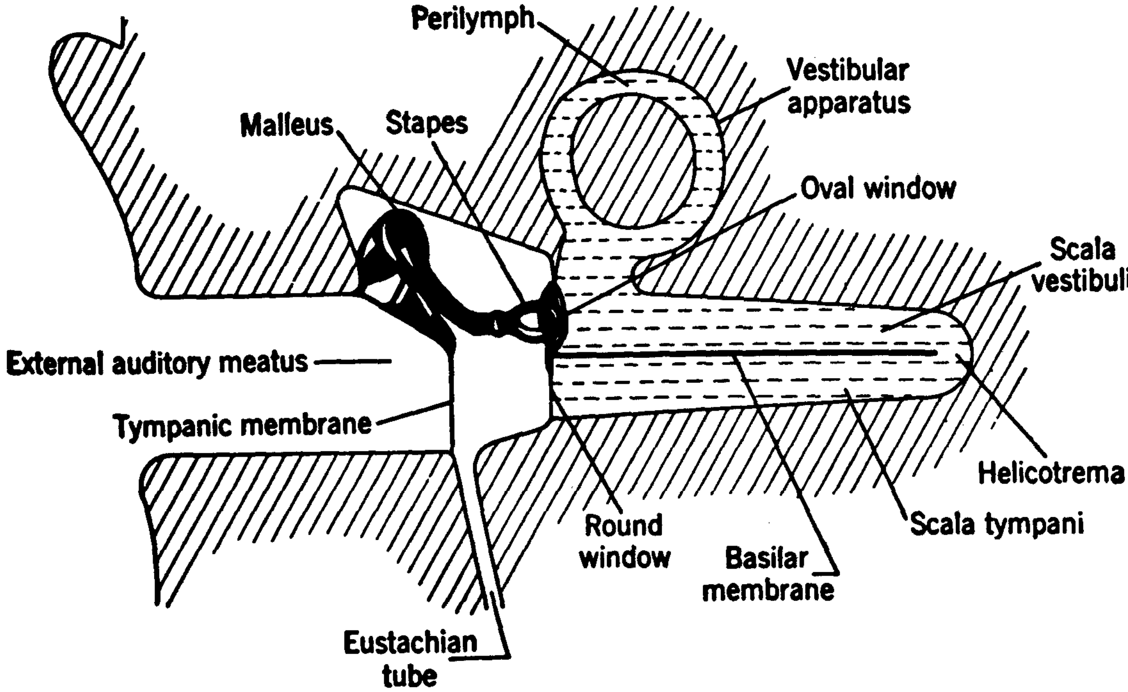

Figure A1.1

Schematic drawing of the human ear. Sound waves enter the external meatus, and move the tympanic membrane which sets the three ossicles in motion. When the stapes footplate moves inward, the perilymph inside the cochlea flows in the direction of the helicotrema and makes the round-window membrane bulge outward. All these movements can be observed with the aid of a microscope. (From Békésy and Rosenblith 3/, and Békésy 4/).

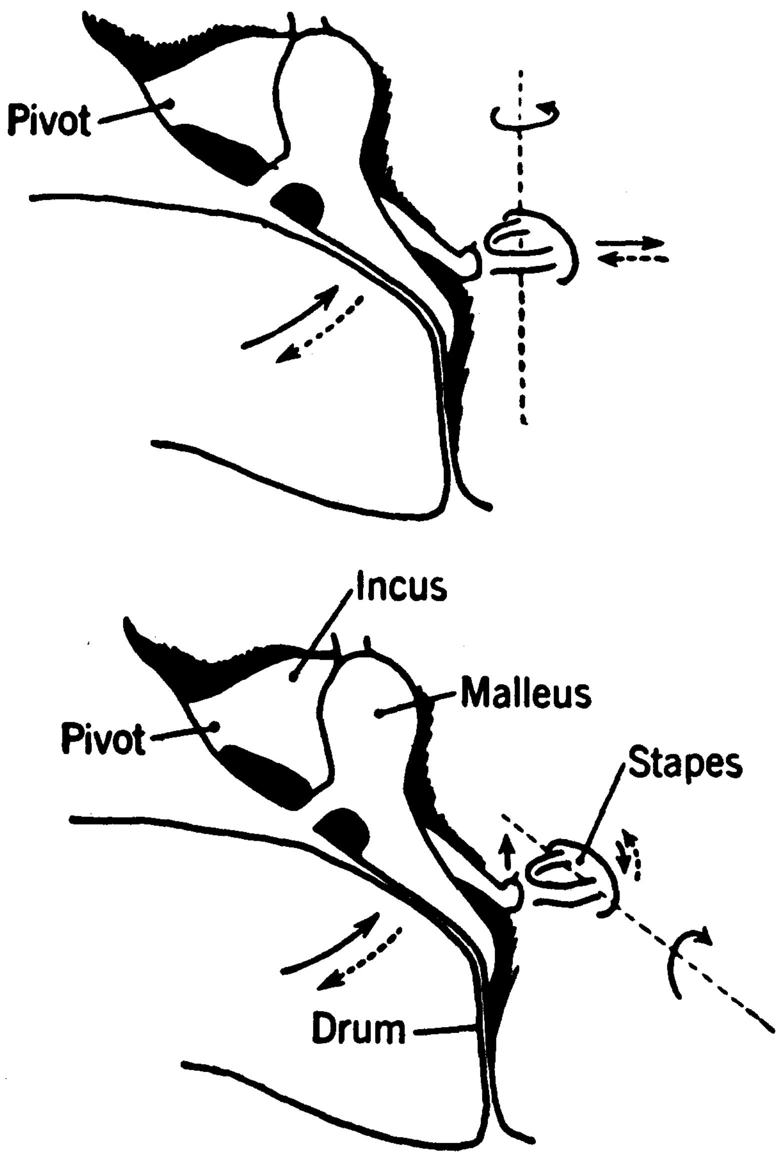

Figure A1.2

The two modes of vibrations of the stapes. (A) Rotation of the footplate about a vertical axis through its far edge occurs in response to weak sounds. The fluid is pressed into the scala vestibuli by the motion of the edge of the stapes nearest the reader. (B) For intensities above the threshold of feeling, the axis of rotation coincides with the longitudinal axis of the footplate, and the actual volume of the fluid pressed into the scala is reduced. (From Békésy and Rosenblith 3/, and Békésy 5/).

relatively little effect in the frequency range above 1000 cps. Also, it takes time for the muscles to respond to high intensity sound. It takes the reflex about 1/100 of a second to become effective. In other words, there is enough time for quite a few high intensity peaks to reach the inner ear before the muscles become effective. While the muscles may provide a reasonable amount of protection for low frequency steady sounds, they are rather ineffective against sudden noises. There is no information on the way in which the muscles behave in the presence of waveforms that exhibit repeated peaks.

The inner ear contains a multitude of cavities and channels whose shapes are sufficiently complex to be known under the technical name of the labyrinth. We shall, therefore, attempt to give only a rather simplified description of details of the cochlea, whose role in the process of hearing in mammals and birds is clearly established. In man, this snail-like coil (hence the name cochlea, which means snail in Greek) is a rather flat spiral of about two and one-half turns. The cochlea is subdivided into three channels, two of which are filled with liquid (see Fig. A1.3). The third channel, the cochlear partition that separates the upper from the lower gallery, is made up of several fibrous flexible membranes including the basilar membrane. It contains also the so-called hair cells, their supporting structures such as the organ of Corti, and the tectorial membrane. The remainder of the space is filled with a highly viscous liquid called endolymph. This middle channel contains in addition the nerve fibers that join to make up the auditory nerve.

In the last decade our knowledge concerning the mechanical events inside the cochlea has advanced greatly. Practically all the information has come from the work of a single man - Békésy*, whose technique is sufficiently refined to enable him to make measurements inside the cochlea without destroying it or without seriously interfering with its functioning. We are now not only able to specify the elastic properties of the structures that make up the cochlea (see reference 3/, Fig. 27) but we can also state what the pattern of vibration along the cochlear partition will be when the ear is stimulated by tones between 50 and about 3000 cps (see Fig. A1.4).

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* For an extensive bibliography of the papers of G. v. Békésy see the references at the end of Chapter 27 of the Handbook of Experimental Psychology.

We thus know that we cannot account for the fine discriminations in pitch of which men and animals are capable on the basis of the resonance of the simple tuned elements that were supposed to make up the basilar membrane. The resonance patterns along the cochlear partition are rather broad and the implication is that we have to look for some mathematical transformation or other mechanism that would produce a considerable amount of sharpening. If we wanted to account for man's discriminatory ability, Békésy's work (and the work of others who have dealt essentially with electrical aspects of the ear's behavior in response to sounds) makes it obvious that the time is past when it is safe to consider an organism's behavior in response to an acoustic stimulus and say, "this is what the ear does". It was precisely this feeling that prompted researchers to look for further events along the auditory pathway from the ear to the brain, events that were related to the reception of sounds. Most of the work done in this area falls into either the domain of electrophysiology or the domain of what might be called experimental anatomy.

The auditory nerve after being formed by the junction of the nerve fibers from all parts of the cochlea, passes through a tunnel in the temporal bone and joins the brain stem. From there, fibers run past a few neural relay stations to the top layer of the brain called the cortex. Little would be gained from going into detail on the anatomy of these pathways or on the various auditory areas in the cortex as shown in Fig. A1.5. Let us, however, stress that there are projections of pathways from either ear to each of the cortical hemispheres and that such multiple pathways and other safety factors insure safe delivery of the stimulus message to the higher centers of the brain. This fact is underlined by the results of removal (ablations) of various parts of the auditory cortex 9/. Simple discriminatory abilities of animals were tested, and were shown to be remarkably unaffected even when rather large parts of the auditory cortex were removed. At the present time we have little explanation for these somewhat startling facts. All we can say is that behavior in response to sound is a complex process and that such behavior is impossible in the absence of the most peripheral portions of the auditory system (i.e., the ear). Without an input mediated by the sense organ there is no output. However, at least parts of the central nervous system can be removed in animals without affecting simple kinds of behavior.

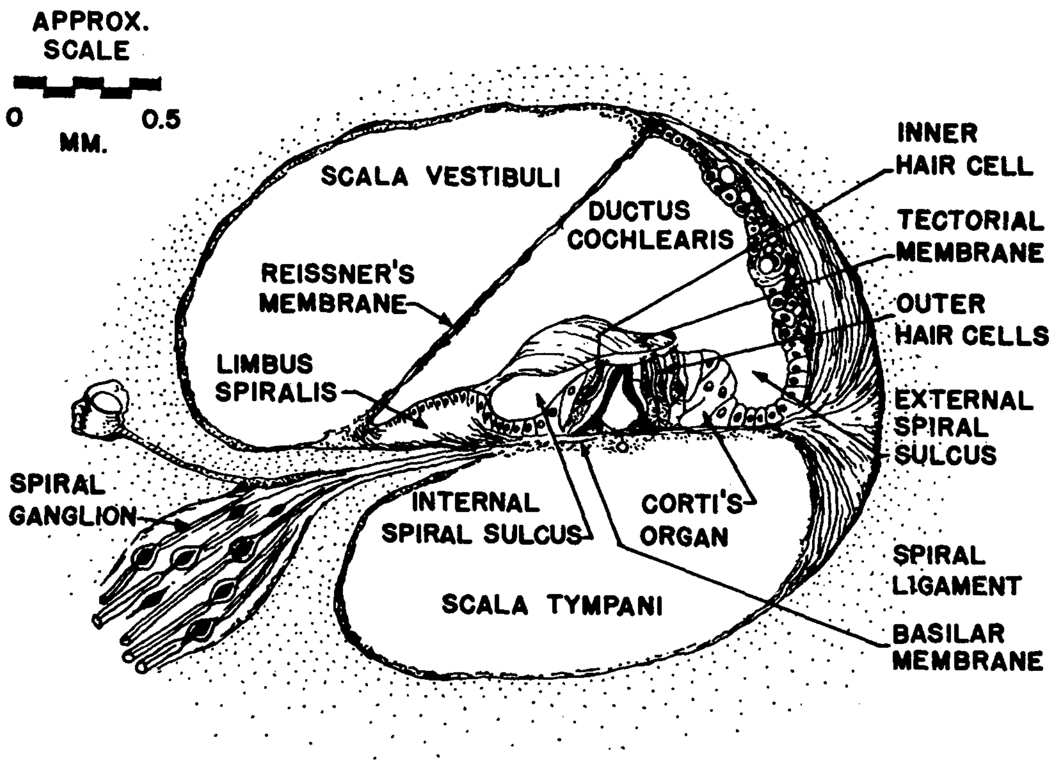


Figure A1.3

Diagrammatic cross-section of a cochlear canal. The cochlear partition includes several fibrous flexible membranes, and contains the hair cells, the ultimate end organs of hearing. (After Davis 6/ and Rasmussen 7/).

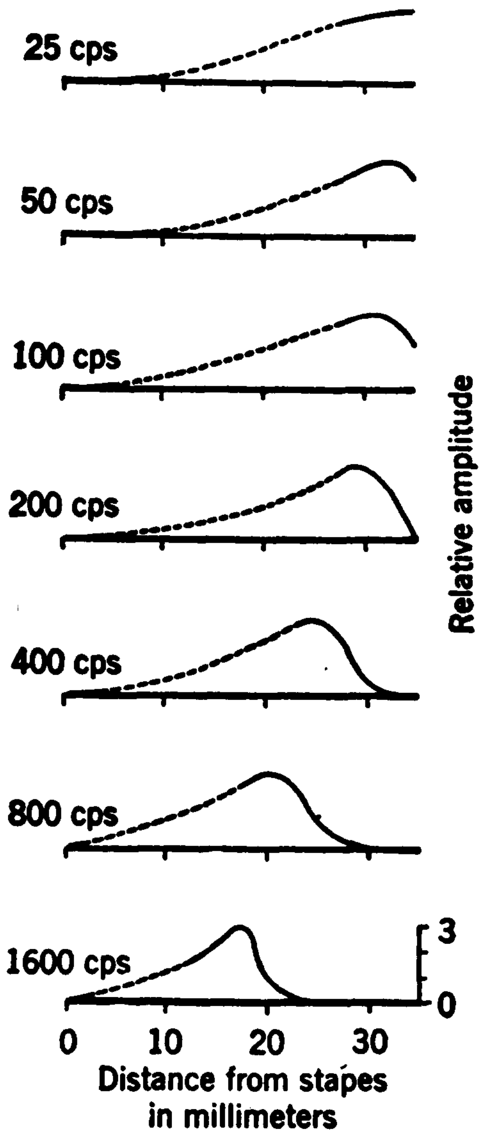


Figure A1.4

Displacement amplitudes along the cochlear partition for different frequencies. The stapes was driven at a constant amplitude and the amplitude of vibration of the cochlear partition was measured. The maximum displacement amplitude moves toward the stapes as the frequency is increased. (From Békésy and Rosenblith 3/, and Békésy 8/).

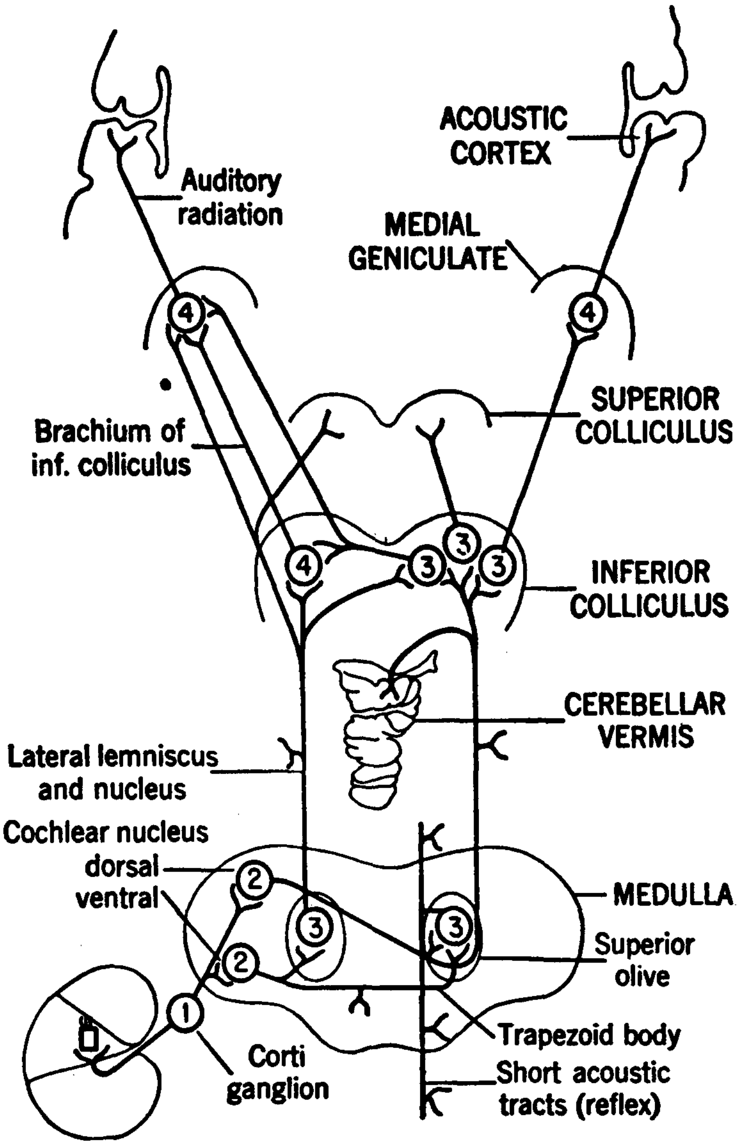
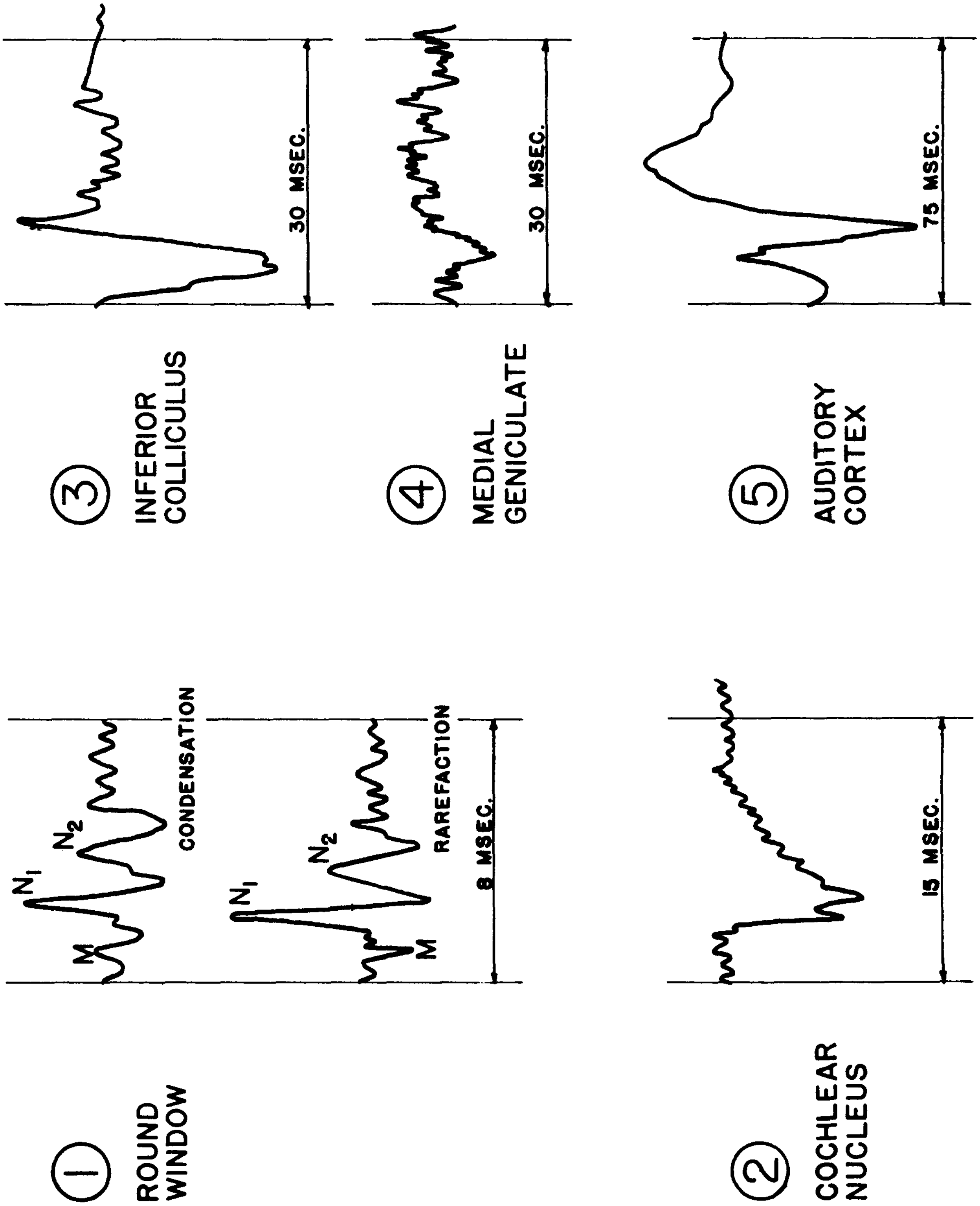


Figure A1.5

The afferent acoustic pathway (based on the cat). The locations of important synapses are indicated in capital letters on the right. The "order" of each neuron is indicated by a number. "Second-order" neurons are separated by at least one synapse from the sense organ.



1
ROUND WINDOW
M
N_1
N_2
CONDENSATION
N_1
N_2
M
RAREFACTION
8 MSEC.
2
COCHLEAR NUCLEUS
15 MSEC.
3
INFERIOR COLLICULUS
30 MSEC.
4
MEDIAL GENICULATE
30 MSEC.
5
AUDITORY CORTEX
75 MSEC.

Within the last two decades many experiments involving electrical responses from various locations of the auditory system have been reported. We cannot attempt to review here the hundreds of papers that have been written. There are, however, a few general facts that have some bearing on the problems with which we are concerned. First of all, we can say that electrical activity starts practically instantaneously in the auditory nervous system after the sound waves impinge upon the eardrum. Typical electrical responses are shown in Fig. A1.6. The delay to the first neural electrical signal is of the order of 1/1000 of a second. The successive locations in the nervous system are activated several milliseconds later and electrical activity at the auditory cortex starts about 1/100 of a second after the initial click sound has been delivered to the ear. These time intervals are remarkable in several respects. The minimum reaction time to a sound stimulus is of the order of 120 to 150 milliseconds 10/. In other words, we can at present account only for a small fraction of the time necessary to elicit behavior in response to acoustic stimuli by what might be called transmission delays in the afferent auditory nervous system. It is clear that it takes time for the muscles to go into operation and it must certainly take time for the activity at the auditory cortex to be translated into activity at the so-called motor cortex. The fact that an animal lifts its right paw in response to an acoustic stimulus is a complex affair; we are certainly not ready to give a neural interpretation of such matters as the comprehension of speech.

Figure A1.6

Tracings of electrical responses to acoustic clicks recorded from various locations of the auditory system (see Fig. A1.5). The records have been taken from the data pool of the Psycho-Acoustic Laboratory at Harvard University; they were taken during the period from 1948 to 1952.

The acoustic clicks are produced by applying electric square pulses of 0.1 millisecond duration to good quality earphones. The sound is conducted from the diaphragm of the phone to the eardrum of the anesthetized animal by means of a small plastic tube. The resonances of the entire system are sufficiently damped in order that the acoustic system as a unit can show a reasonably flat coupler response over a range of about 5000 cps. The coupler cavity is of the order of one cc for animals like cats and monkeys. Under these circumstances most of the energy in the click is delivered to the animal in about one millisecond.

There is, however, good reason to assume that the animal's electrical responses are mainly a function of the initial step in the acoustic click.

The responses at locations 1 and 5 were recorded by fine platinum wire electrodes; those at locations 2, 3 and 4 were obtained with high impedance micro-electrodes (micro-pipettes whose diameter was of the order of 5 micra). The responses shown are the earliest deflections that follow delivery of the stimulus. Various experimenters have shown that response activity continues sometimes for appreciable fractions of a second, and in particular that response to the second of a pair of clicks will be affected during these time intervals. The absolute size of any of the recorded deflections depends on many variables and is as such not of particular interest. At all locations the size of the deflections in general increases as the intensity of the stimulus increases; maximum deflections are usually of the order of several hundred microvolts.

Responses to acoustic clicks have been recorded in cats,monkeys, guinea pigs, hamsters, bats and pigeons (with the exception of location 1 the above traces come from cats; the records at location 1 come from a pigeon). In these animals responses from comparable locations exhibit, in general, similar patterns and are characterized by similar delays, provided the animal's body temperature is normal. Response to clicks are visually detectable at all locations of the auditory nervous system while responses to pure tones do not exhibit this property except at the most peripheral locations. This statement should not be interpreted to mean that there are no responses to pure tones at the auditory cortex, but only that they are not easily detected with our present methods of recording. Responses to clicks can also be shown to be sensitive to "masking" by noise and exposure to intense sound (see Rosenblith 11/).

Note how the response traces of location 1 illustrate the way in which responses to condensation clicks differ from rarefaction clicks (in the first instance the diaphragm of the earphone starts by moving inward while in the case of the rarefaction click it starts by moving away from the eardrum). The earliest deflection at this location, labeled M, is the most prominent component of the so-called cochlear microphone. These microphonic potentials generated in the inner ear of the animal are useful monitors of the acoustic stimulus. Their name refers to what was believed to be the microphonic action of the cochlea in contradistinction to the electrical activity labeled N that originates in neural structure situated near the end organ.

When the ear of an animal is exposed to strong sound, certain parts of the neuro-electric response to a standard click stimulus which follows the strong exposure are depressed for time intervals that depend on the severity of the exposure, i.e., on the sound pressure level of the stimulus, its spectrum and the time during which the stimulus is on (see Fig. A1.7). When the exposure becomes severe enough, this depression of the response becomes irreversible and indications appear that there may have been structural damage inflicted upon certain parts of the cochlear partition. There is a rather vague general relation which indicates that those regions of the cochlea show degeneration that are more directly involved in the reception of high frequency sounds. Certain studies on aged patients at the Johns Hopkins Hospital have resulted in similar findings for what were apparently advanced cases of presbycousis 12/. Studies of a similar type on animals are helpful though it is not really safe to extrapolate in order to estimate what might happen in the case of man. For there is not only much variability in man's reaction to high intensity sounds but it is also by no means certain that the action of the middle ear muscles in animals and men have the same or even comparable effects. There are also many instances in which animal's responses to sound have been irreversibly affected by exposure to loud sounds without the investigator being able to demonstrate definite structural damage by histological techniques.

Electro-physiological studies on animals concerning reversible auditory fatigue (the depression in response to a click) confirm what we know already from human audiograms. Loss of function in one ear leaves the performance of the other ear untouched 13/.

Contrary to popular belief, the eardrum seems to play a relatively small role in damage produced in the auditory mechanism by the exposure to high intensity sounds. We know from various researches that a small hole in the drum will have little effect on hearing and perhaps more important, the drum is in some sense a safety device which will only go into action for explosions that last a relatively long time, i.e., in which the low frequency components are prominent. It is in this latter circumstance that the drum may be torn and damage may even be caused to the ossicles. This loss of drum and perhaps of part of the ossicular chain reduces the amount of sound energy transmitted to the inner ear.

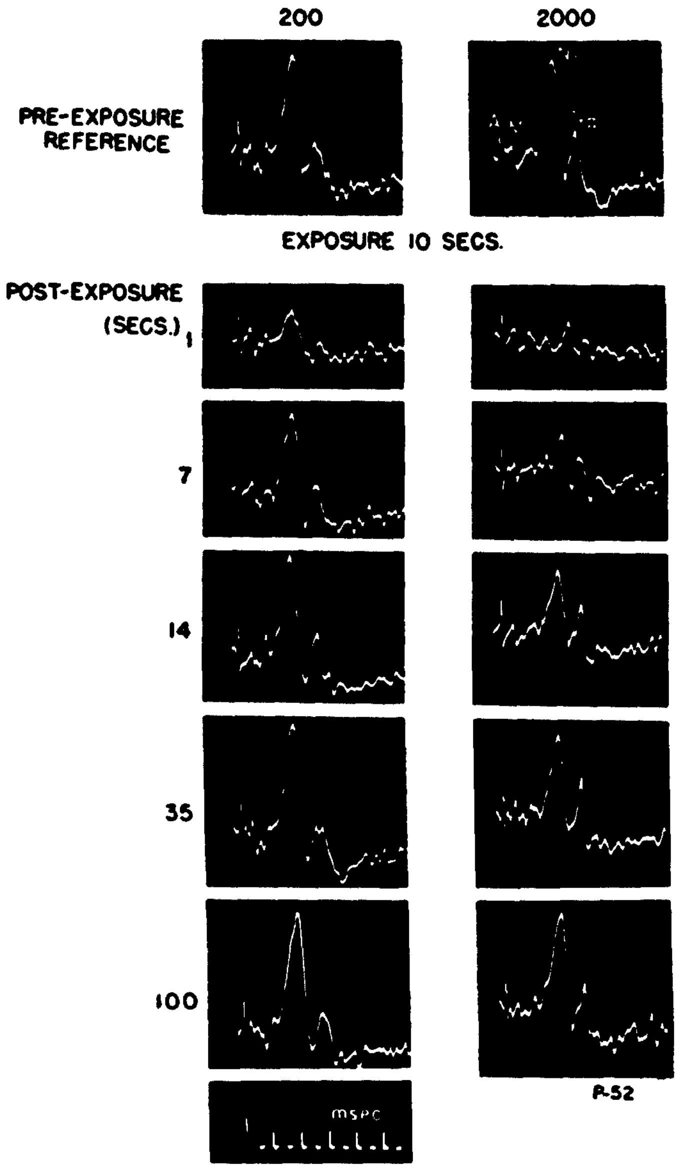


Figure A1.7

Effect of exposure to loud tones on the response to clicks as recorded from the round window. The top line shows typical responses to weak clicks (about 15 db above human threshold). The lower pictures are for various time intervals after exposures to tones of 200 and 2000 cps for 10 seconds at a sound pressure level of about 105 db. (1) Both neural components are reduced in approximately the same proportions; (2) recovery is quicker after exposure to the 200 cps tone, and the first neural component becomes supernormal; (3) the latency of N is increased in the early stages of recovery after the 2000 cps exposure. (From Rosenblith 11/).

Appendix 1

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APPENDIX 2

Properties of Ear Protectors or Aural Protective Devices

There are many industrial and military situations in which personnel must be present in a high-intensity sound field in order to perform their tasks properly. It may not be practical or even possible to reduce the sound pressure level by control of the noise at the source or by protecting the individual by a shield or enclosure. Under these circumstances, it is possible to reduce the amount of sound energy reaching the ears of the individual by the use of ear protectors. During World War II intensive research was done in this area (see Shaw, Veneklasen, Stevens et al 1/).

By far the major portion of the sound energy that reaches the inner ear is transmitted via the ear canal, the eardrum and the ossicular chain. The usual types of ear protectors are devised to minimize the amount of sound energy transmitted by this path. This path is usually called the air conduction path, in contrast to the bone conduction* path through the bones of the head.

Even though transmission by air conduction may be reduced to a negligible value, sound energy may still be transmitted through the bones of the head to the cochlea. It has been shown 4/ that for persons with normal hearing at certain frequencies in the middle range bone-conducted energy is at least 50 db below the energy transmitted by air conduction. Thus there is an upper limit to the effectiveness of ear protectors that are designed to reduce the air-borne sound energy. Such protective devices cannot be expected to decrease the sound energy reaching the inner ear by more than about 50 db, when the head of the individual is in the sound field. Actually, other considerations seem to limit the effective transmission loss to something less than 50 db.

There are three general methods of occluding the ear with devices that attenuate air-borne noise: (1) substances inserted into the ear canal, so-called "insert types," (2) objects covering at least the entrance to the ear canal, and often the entire outer ear, so-called "cushion" or "doughnut types,"

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* The most important sources of information on bone conduction are Barany's monograph 2/ and several articles by Békésy 3,4,5/.

(3) fitted coverings for the major or entire area of the head, so-called "helmet types."

Insert types include malleable substances that can be molded by the wearer to fit his own ear; formed soft rubber plugs either vented or unvented; hard plastic substances preformed to approximate average canal dimensions and contours; permanent molds of individual canals made from casts; metal and soft rubber plugs with valves designed to close only at high sound pressure levels; formed soft rubber plugs with metallic weights which increase the mass.

Cushion or doughnut types include kapok-filled toroids, such as the familiar "doughnut type" earphone socket used in flying helmets; round rubber enclosures containing perforated discs which help to discriminate against certain portions of the audible frequency range; ovoid sponge rubber sockets mounted in a plastic shell; round rubber sockets, lined with metal and acoustic absorbent substances. All of these devices are kept in place by headbands.

Helmet types include flying helmets with earphone cushions, and crash helmets. Some effort is at present being devoted to producing a helmet with high noise-attenuation properties. Such a helmet must enclose the entire head, including the face, in order to reduce the sound energy transmitted to the bones of the head, as well as the energy transmitted through the normal air conduction path.

It is clear that both helmet and doughnut type ear protectors can be combined with the insert type.

Provided personnel have been trained to accept and wear ear protection, the most important criterion* by means of which the effectiveness of such devices is measured is the reduction of sound energy (usually expressed in decibels) that is provided. The reduction must be specified as a function of frequency, since it is, in general, different for diverse frequencies.

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* Other criteria, to be considered later, include such considerations as comfort, ease of insertion and removal, and freedom from the possibility of infection.

There are several methods of measuring the performance of ear protectors. Some methods involve testing by physical means only, whereas others involve psycho-acoustic measurements. Each method is discussed briefly below.

1. In the physical procedure, a small enclosure or coupler containing an aperture is used to test the ear protector. If an insert type is to be tested, it is inserted into the aperture; if a cushion type is to be tested, it is mounted over the aperture. A loudspeaker or other sound generator is mounted outside the enclosure, and a microphone is used to measure the sound pressure inside the enclosure. The loudspeaker-microphone system is first calibrated with the aperture open. Then the ear protector is placed in or over the aperture, and the reduction is measured. There is, of course, an upper limit to the measurable transmission loss, determined by the transmission loss of the walls of the enclosure and microphone.

The physical procedure does not take into account the variables encountered when protectors are placed in or over human ears. Ears vary considerably in size and shape, and hence, there are considerable differences in the fit of the same devices used in different ears. Thus there is some variation in effective transmission loss in practice. However, the physical measurement procedure should provide a reasonably reproducible technique for the evaluation of the relative attenuation provided by various types of protectors - a technique that could be standardized. For some applications, therefore, the procedure is useful, though problems of fit in the ear canal and static pressure on the ear drum have to be considered when physical and psycho-acoustic measurements are compared.

2. Two psycho-acoustic procedures have been used in order to measure the protection provided by the above mentioned devices. The usual method is to measure the subject's absolute threshold of hearing when he is wearing protectors and when he is not. The difference is the attenuation afforded by the device. More realistic data are obtained if free-field measurements are made, but reasonable results for plugs (but not for cushion type defenders) may be obtained if the signal is presented through earphones.

A second procedure that is occasionally used is a loudness balance technique. A tone is presented to a listener first without ear protectors and then with protectors. The

intensity of the tone in the second case is raised until the subject judges it to be as loud as the tone he heard without ear protection. The increase in intensity at any given frequency is equal to the attenuation provided by the device. In practice the usual procedure is to present the tone through earphones. The plug is placed in one ear only, and the relative signal levels at the two earphones are adjusted until the subject judges the tones at the two ears to be equally loud. The difference in signal level at the two ears (assuming identical performance of the two ears, and that is an assumption that ought at least to be checked) is the attenuation of the plug. Such binaural loudness balance techniques are not without pitfalls (see Garner 6/).

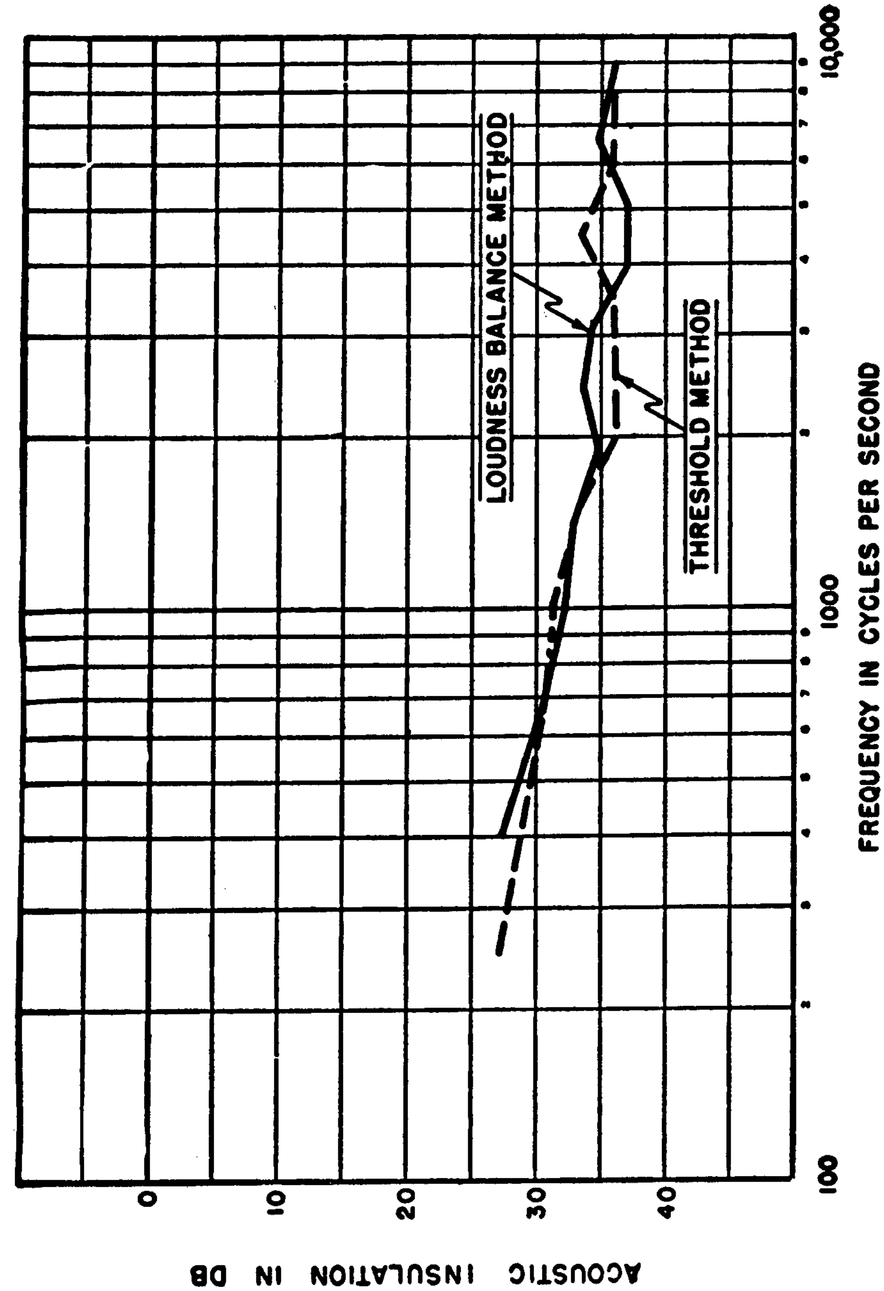
Figure A2.1 shows an experimental comparison of the threshold shift and loudness balance techniques for one type of ear protector.

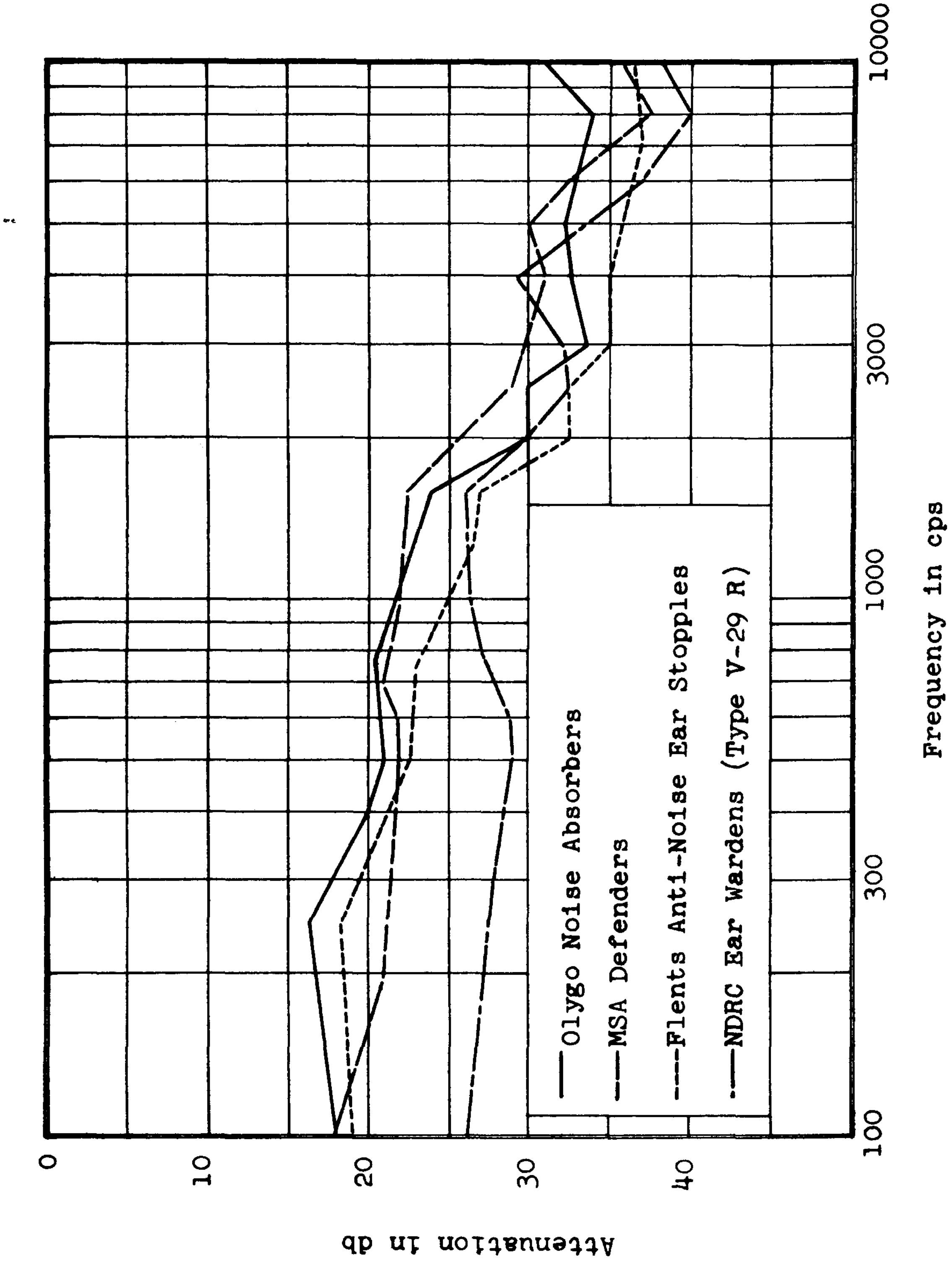
Miller, Weiner and Stevens 7/ have summarized measurements of threshold shifts for various types of aural protective devices. Some of their data are shown in Fig. A2.2, plotted in the standard form of audiograms. Most of the devices give an attenuation of 15-25 db at 100 cps. The attenuation gradually increases to a maximum of 30-40 db at high frequencies. The perfection of fit of the plug has a marked effect upon the attenuation. The data of Fig. A2.2 represents the probable maximum attenuation obtainable with well-fitting plugs of the types indicated.

The attenuation for well-fitting cushion type defenders is the same order of magnitude as that of plugs. However, if plugs are used in conjunction with cushion type defenders, a higher attenuation can be obtained. It is believed that this combined protection approaches the theoretical limit imposed by bone-conducted sound. Greater attenuation can be obtained only by completely enclosing the head with a helmet constructed from a material that provides adequate transmission loss.

Figure A2.1

A comparison of the attenuation for one type of ear protector measured by the threshold shift and loudness balance technique (From Miller, Wiener and Stevens 7/).


LOUDNESS BALANCE METHOD
THRESHOLD METHOD
FREQUENCY IN CYCLES PER SECOND
100
1000
10,000
ACOUSTIC INSULATION IN DB
0
10
20
30
40



Olygo Noise Absorbers
MSA Defenders
Flents Anti-Noise Ear Stopples
NDRC Ear Wardens (Type V-29 R)
Frequency in cps
Attenuation in db
0
10
20
30
40
100
300
1000
3000
10000

The use of defenders effectively gives to the wearer a temporary conductive type hearing loss. This is illustrated in Fig. A2.3, which indicates a subject's threshold with and without a protective device. The audiograms were obtained by means of a continuous recording audiometer. The remarks in Sec. 16.3 on conductive deafness will apply, therefore, to the situation in which protective devices are used. In particular, the comments on speech perception are pertinent.

The effect of wearing plugs on the intelligibility of speech in noise has been tested experimentally 8,9/, and the results are presented in Fig. A2.4. The intelligibility of faint speech sounds in the quiet is greatly reduced by the plugs. For very intense speech, certain experimenters have shown a drop in articulation score in the absence of noise. No such decrease was observed with plugs 8/. As the level of the masking noise is increased to a point where the effective masking of the speech is 60 db or more, ear protectors do not interfere with speech reception. In fact, the data show that for high noise levels, the wearing of earplugs actually improves the intelligibility of speech in noise. This could be attributed to the fact that the plugs do not alter the signal-to-noise ratio, but merely lower the effective level of both the speech and noise by about 20 db. This fact is of some practical importance, since it indicates that, besides providing protection against high-intensity noise, ear protectors improve the ability of the wearers to receive instructions or orders in the presence of noise.

In a recent report on Problems of High Intensity Noise 10/ several practical considerations that have interfered with the general use of ear protection are examined. The following discussion reproduces some of the practical points raised by Rosenblith, Wheeler and Smedal.

Figure A2.2

Attenuation in decibels provided by various types of ear protectors (insert type). The attenuation is determined by measuring the threshold shift that occurs when the ear is plugged. (After Miller, Wiener and Stevens 7/, and Kryter 9/).

1. Size. Among men, ear canals differ considerably in cross-sectional area 1/. They differ also in the direction and tortuosity of their course leading to the tympanic cavity. As a result, the problem of "fitting" the individual is the first problem encountered in promoting the use of ear protection. The individually molded substances offer no difficulty here. The soft rubber forms are usually supplied in several sizes, from which the individual is expected to select the size that fits his ear canals best. Guidance should be given at this point because men frequently choose, for reasons of comfort, sizes smaller than correct. A protector that is too small loses much of its value because even slight leaks decrease the protection.

2. Comfort. Ear protectors are not necessarily uncomfortable, but the fact should be faced frankly that, with many men, the first complaint is likely to be that of discomfort. Often, however, this stems from a desire to avoid using the protection rather than from true physical discomfort or pain. In the matter of comfort, the best procedure seems to be that of having a man choose the type of protector, as well as the size he prefers. It is often good policy to have several types of protectors available rather than to fix on one which is supposedly "the best." Among the several protectors that are acceptable, there is relatively little difference in the attenuation they yield. These differences are minor compared to the difference between protection and no protection.

3. Distribution. The best hearing-conservation programs will distribute protectors under the supervision of persons who have both interest and experience in the use of ear protection. In the Services, this person might typically be a medical officer, a nurse, or even a hospital corpsman. The indiscriminate offering of protectors usually leads to a high

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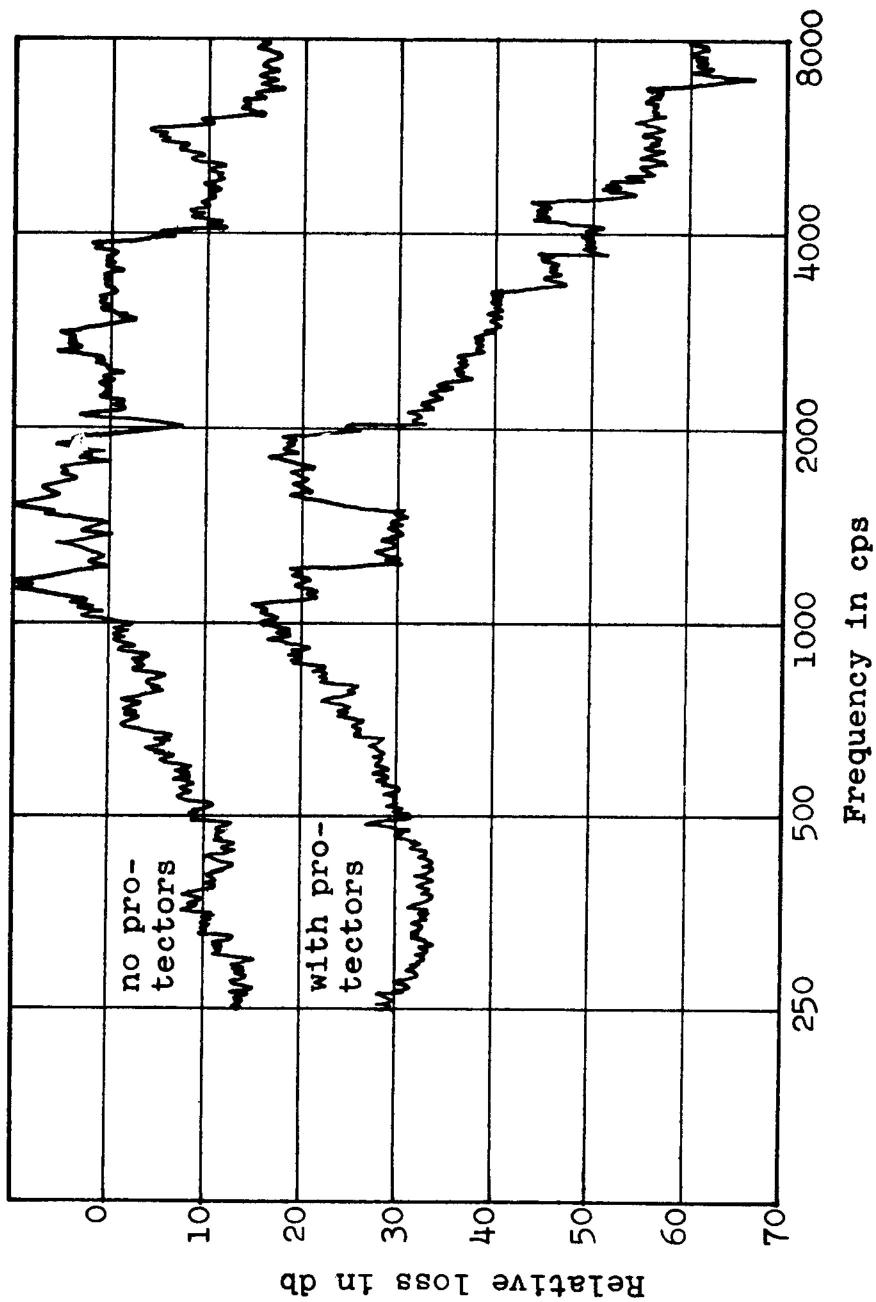
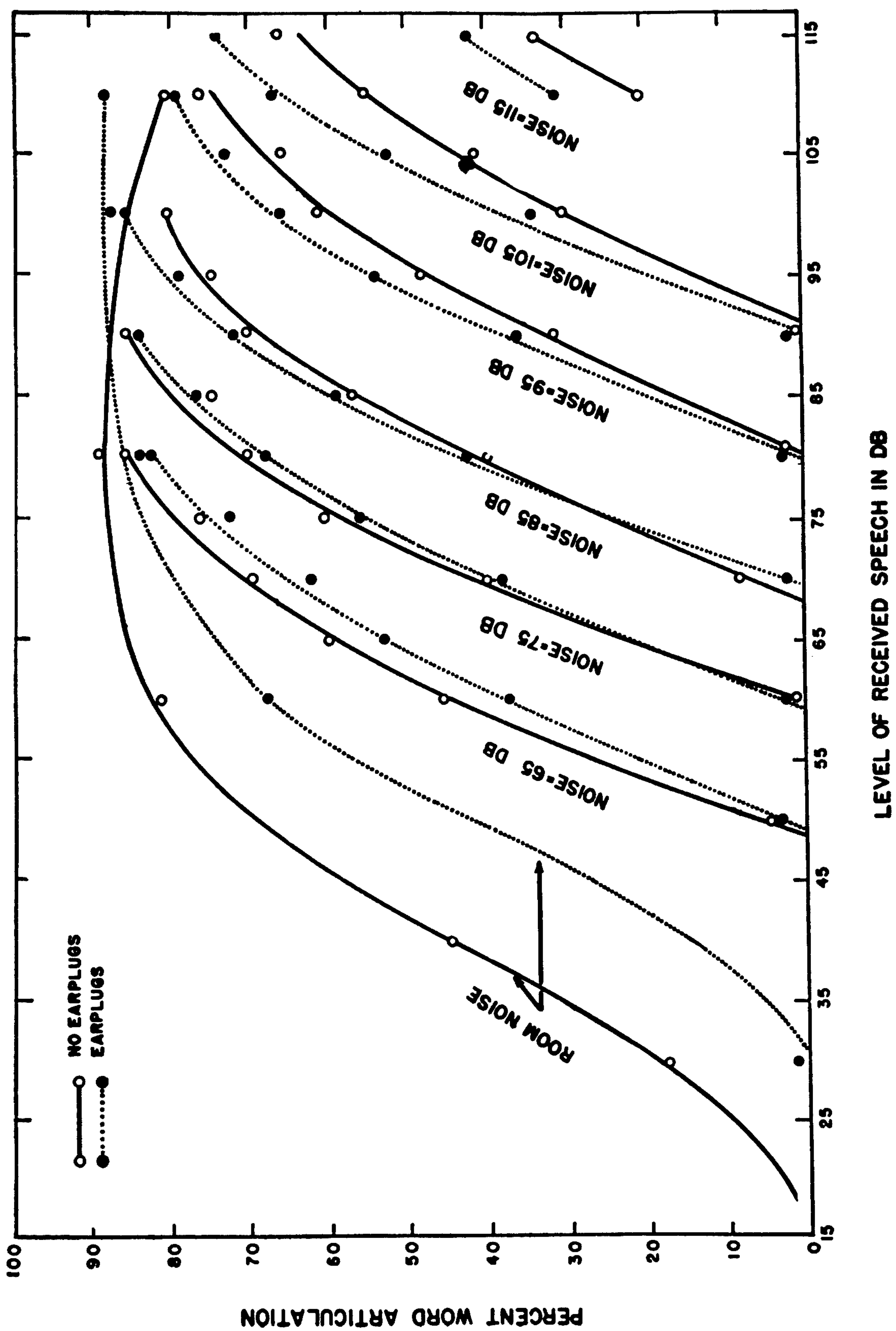
Figure A2.3

A subject's thresholds with and without a protective device are shown by two curves. The audiograms were obtained by means of a continuous recording audiometer. The difference between the two curves at any one frequency gives the loss provided by the plug at that frequency. (From an unpublished paper by D. E. Wheeler, personal communication).



no pro-
tectors
with pro-
tectors
Frequency in cps
250
250
500
1000
2000
4000
8000
Relative loss in db
0
10
20
30
40
50
60
70



NO EARPLUGS
EARPLUGS
ROOM NOISE
NOISE=65 DB
NOISE=75 DB
NOISE=85 DB
NOISE=95 DB
NOISE=105 DB
NOISE=115 DB
PERCENT WORD ARTICULATION
LEVEL OF RECEIVED SPEECH IN DB
0
10
20
30
40
50
60
70
80
90
100
15
25
35
45
55
65
75
85
95
105
115

number of rejections unless some guidance is offered; demonstrations of how they are inserted and removed, of how to select the best size for each man, some discussion of what protectors will and will not do, all contribute to a man's acceptance of ear protection. Because certain diseases of the ear are encountered that make the use of insert type protectors undesirable, inspection of the canals ought to be carried out by someone competent to recognize possible complications. Ordinarily, this is a matter for medical supervision.

4. Care and upkeep. Most protectors are not fragile, nor do they deteriorate rapidly with usage. The manufacturer usually supplies a convenient carrying case that also prevents gross contamination when the protectors are not in use. The permanent types are washable. Regular cleaning of the protectors adds to their useful life, and cleaning is, of course, an obvious requirement from the standpoint of hygiene. A contaminated insert type, or one that has an accumulation of hardened wax, presents a rough surface to the lining of the ear canal. Protectors left in such a condition are unnecessarily uncomfortable and, if repeatedly used, might very well contribute to an external otitis. For these reasons, medical supervision is indicated in the fitting of ear protection and in providing the necessary instruction and indoctrination.

When flight personnel wear plugs, they should be cautioned of the possible effects of a rapid decrease in altitude*. The resulting unequal pressure on the two sides of the plug may tend to push the plug into the ear canal, with possible damage to the canal and to the tympanic membrane. The flyers should be cautioned to loosen the plugs before descending, or to wear plugs that have a small hole for purposes of pressure equalization.

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* Personal communication from Major Elizabeth Guild, USAF.

Figure A2.4

The relation between the percentage word articulation and the speech level with and without earplugs. The parameter is the level of the masking noise. NDRC "type V-51R" earplugs were used. The data show an improved intelligibility in the presence of intense noise. (From Kryter 8/).

Appendix 2

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